Acquisition Directorate
Research & Development Center

Report No. CG-D-01-23

Lifesaving Equipment Colors; Literature Review

Distribution Statement A: Approved for public release; distribution is unlimited.

July 2023

Homeland Security

N O T I C E

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Technical Report Documentation Page

1. Report No.	2. Government Accession Number	3. Recipient's Catalog No.
CG-D-01-23		
4. Title and Subtitle Lifesaving Equipment Colors; Literature Review		5. Report Date July 2023 6. Performing Organization Code Project No. 1032
7. Author(s) J. Pennington, J. Peterson		8. Performing Report No. RDC UDI # 2025
9. Performing Organization Name and Address U.S. Coast Guard Research and Development Center 1 Chelsea Street New London, CT 06320		10. Work Unit No. (TRAIS) 11. Contract or Grant No.
12. Sponsoring Organization Name and Address COMMANDANT (CG-ENG-4) US COAST GUARD STOP 7506 2703 MARTIN LUTHER KING JR AVE SE WASHINGTON, DC 20593		13. Type of Report & Period Covered Interim, October 2022 – July 2023 14. Sponsoring Agency Code Commandant (CG-ENG-4) US Coast Guard Stop 7509 Washington, DC 20593
15. Supplementary Notes The RDC's technical point of contact is Mr. Joshua Pennington, 860-271-2866, email: Joshua.D.Pennington2@uscg.mil.		
16. Abstract (MAXIMUM 200 WORDS) The U.S. Coast Guard (USCG) Research and Development Center (RDC) conducted a review of lifesaving equipment color requirements as well as the relationship between color and visual search. The purpose of this report is to consolidate information on the current state of lifesaving equipment color requirements, including research on color characteristics (and the human response thereto) that enhance the probability of detection by visual search. Provided herein is a summary of domestic regulations, international conventions, and government and industry standards that provide prescriptive or performance requirements for lifesaving equipment colors. In addition, it includes a literature review of peer-reviewed research on color conspicuity, detectability, and visual search theory. The regulatory, standards, and literature reviews will provide information on target color selection, psychophysical effects impacting visual search, and recommendations for future research. This information and resultant conclusions will inform RDC for experimental test plan development to verify and/or determine optimally detectable lifesaving equipment colors.		
17. Key Words Chromaticity, color, conspicuity, high visibility, detectability, fluorescent, guidance, lifesaving equipment, luminance, maritime, psychophysical, salience, search and rescue, visual search	18. Distribution Statement Distribution Statement A: Approved for public release; distribution is unlimited.	

19. Security Class (This Report)	20. Security Class (This Page)	21. No of Pages	22. Price
UNCLAS\\Public	UNCLAS\\Public	44	

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EXECUTIVE SUMMARY

The U.S. Coast Guard (USCG) Research and Development Center (RDC) conducted a review of domestic regulations, international conventions, and government and industry standards that provide prescriptive and performance requirements for lifesaving equipment colors as well as a literature review of peer-reviewed research on color conspicuity, detectability, and visual search theory. The purpose of this report is to consolidate information on the current state of lifesaving equipment color requirements, including research on color characteristics (and the human response thereto) that enhance the probability of detection by visual search.

As the nation's lead maritime regulating body, the USCG is charged with promulgating regulations that support its eleven statutory missions. One of these missions – Marine Safety – includes the approval of lifesaving equipment intended for use on commercial vessels. Title 46 Code of Federal Regulations (CFR) Subchapter Q contains strict prescriptive and performance requirements to which equipment must be manufactured and independently tested prior to receiving Coast Guard (CG) approval; one of those requirements is color. Currently, permitted colors for CG-approved lifesaving equipment are variations of orange or reddish orange, including Indian Orange, International Orange, Scarlet Munsell 7.5 Red 6/10, and Vivid Reddish Orange (or a fluorescent color of similar hue). The decision to select these colors originated from a 1955 United States Navy (USN) research project that determined orange (and similar hues) was the most detectable color in the largest variety of weather and light conditions.

In 2012, the International Maritime Organization (IMO) published unified interpretation MSC.1/Circular 1423 – *Unified Interpretation of Paragraph 1.2.2.6 of the Lifesaving Appliances Code (LSA) Concerning Lifeboat Exterior Color*, which permitted Member Governments to accept a comparably "highly visible colour" for lifeboat exteriors in lieu of the International Orange or Vivid Reddish Orange specified by the LSA. In accordance with the circular, several member governments approved or requested approval of alternative colors for lifeboat exteriors, particularly for large passenger vessels and cruise ships. These actions have been a catalyst for increased requests to the USCG to accept alternative colors for lifeboats as well as other CG-approved lifesaving equipment, with some members of the IMO and maritime industry citing the U.S. Navy's 1955 study as archaic.

The CG has committed to ensuring that any lifesaving equipment colors other than those specified by the CFR, International Convention for the Safety of Life at Sea (SOLAS), LSA Code, or accepted by the CG prior to the issuance of MSC.1/Circ. 1423, provide a level of safety equal to or exceeding the previously approved hues of orange. To that end, the Lifesaving and Fire Safety Division (CG-ENG-4) in the Office of Design and Engineering Standards at Coast Guard Headquarters (CG-ENG) sponsored an RDC project to verify optimal color(s) for CG-approved lifesaving equipment. This review document is the first product of that project.

RDC will use knowledge gained from this review to develop an experimental test plan to determine and validate optimally visible colors in the marine environment. RDC staff assessed domestic policy and regulations, international conventions, industry standards, and peer-reviewed literature to identify specific colors and color characteristics for further evaluation. The colorfastness of fluorescent color dyes and paints has substantially improved since preliminary studies in the 1950's. As such, the colors recommended for experimental testing are Fluorescent Green, Fluorescent Orange, Fluorescent Pink, and Fluorescent Red, with International Orange designated as the control.

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LIST OF ACRONYMS, ABBREVIATIONS, AND SYMBOLS

°	Degrees
§	Section
ANSI	American National Standards Institute
ASTM	ASTM International (formerly American Society for Testing and Materials)
CFR	Code of Federal Regulations
CG	Coast Guard (synonymous with United States Coast Guard)
CIE	International Commission on Illumination
Circ.	Circular
DOT	Department of Transportation
ed.	Edition
e.g.	"Exempli gratia"/for example
FAMA	Fire Apparatus Manufacturers' Association
FED-STD	Federal Standard
ft	Feet
HVSA	High Visibility Safety Apparel
IACS	International Association of Classification Societies
IALA	International Association of Marine Aids to Navigation and Lighthouse Authorities
i.e.	"Id est"/in other words
IMO	International Maritime Organization
in	Inch
ISEA	International Safety Equipment Association
ISO	International Organization for Standardization
km	Kilometer
LE	Law Enforcement
LSA	International Lifesaving Appliance Code
m	Meter
mi	Mile
MILSPEC	Military Specification
MITAGS	Maritime Institute of Technology and Graduate Studies
MSC	Maritime Safety Committee
MUTCD	Manual on Uniform Traffic Control Devices
NBS	National Bureau of Standards
n.d.	No date
NFPA	National Fire Protection Association
nm	Nanometer
OSHA	Occupational Safety and Health Administration
Para.	Paragraph
PFD	Personal flotation device
PIW	Person(s) in the water
PSC	Port State Control

LIST OF ACRONYMS, ABBREVIATIONS, AND SYMBOLS (Continued)

RDC	Research and Development Center
SAE	SAE International (formerly Society of Automotive Engineers)
SCCA	Standard Color Card of America
SOLAS	International Convention for the Safety of Life at Sea
UI	Unified Interpretation
UL	UL Solutions (formerly Underwriters Laboratories)
U.S.	United States
USC	United States Code
USCG	United States Coast Guard
USN	United States Navy
UV	Ultraviolet
WPI	Worcester Polytechnic Institute

1 INTRODUCTION

United States Coast Guard (USCG) missions are interconnected such that actions supporting one mission directly or indirectly affect other missions. Consequently, the USCG conducts a thorough analysis when new regulations, or modifications to existing regulations, are proposed to ensure they maintain a standard of safety, equal to or greater than what previously existed. For instance, the Search and Rescue (SAR) mission includes searching for and rescuing persons in the water (PIW), while a facet of the Marine Safety mission is approving lifesaving equipment intended for use on watercraft (Figure 1). While many modes of electronic detection exist, visual detection by SAR responders remains the primary means of locating PIW. Changes to physical or performance characteristics of approved lifesaving equipment by Marine Safety policy offices could impact SAR responders' search performance to detect and rescue PIW.

Figure 1. Example of USCG-Approved Type I commercial life jacket (West Marine, 2023).

1.1 Background

Countries that engage in maritime trade promulgate shipping regulations to ensure the safety of their merchant fleets. In the United States, shipping regulations are contained in the Code of Federal Regulations (CFR). Ships engaged in international trade must comply with both the regulations of their flag state (i.e., the country where the vessel is registered) and, if their flag state is signatory, the standards set forth in the International Convention for the Safety of Life at Sea (SOLAS) (IMO, 2023). According to the International Maritime Organization (IMO), there are 168 countries signatory to SOLAS, constituting 99% of the world's shipping tonnage (IMO, 2023).

Foreign flagged passenger vessels (e.g., cruise ships) carrying a United States (U.S.) citizen as a passenger, or boarding passengers from a U.S. port, are not permitted to depart that port if the vessel fails to comply with SOLAS standards applicable to U.S. vessels (Shipping, Title 46 United States Code [USC] § 3505, 2021). Foreign vessels flagged in countries having inspection standards comparable to the United States, and holding a current inspection certificate from that country, are subject to inspection by the USCG to verify compliance with SOLAS (Shipping, Title 46 USC § 3303, 2021). USCG Port State Control (PSC) officers are tasked with conducting initial and annual verification exams for this purpose.

Among the multitude of international conventions and U.S. regulations PSC officers verify for compliance the International Life-Saving Appliance (LSA) Code, which establishes the minimum safety standards for lifesaving equipment required by Chapter III of SOLAS. The LSA Code addresses equipment including personal lifesaving gear, visual signals, survival craft, rescue boats, launching and embarkation systems, and other related lifesaving appliances. The general requirements for lifesaving appliances are specified in Chapter I, Section 1.2; of particular interest is Paragraph (Para.) 1.2.2.6 which states "…all life-saving appliances prescribed in this part shall… be of international or vivid reddish orange, *or a comparably highly visible colour* on all parts where this will assist detection at sea" (LSA Code, 1996 [Amended 2017]).

In 2012, the IMO Maritime Safety Committee (MSC) published Circular (Circ.) 1423 providing a unified interpretation of the LSA Code Para. 1.2.2.6 specific to lifeboat exterior colors. The circular defined "highly visible colour" as "colours of strong chromatic content, i.e., pure achromatic colours such as white and all shades of grey should not be accepted as 'comparable' colours", and encouraged Member Governments to use this interpretation when applying the provisions of the LSA Code to lifeboat exterior colors (IMO MSC, 2012). In short, MSC.1/Circ. 1423 permitted countries to approve lifeboat colors other than orange hues. This interpretation is problematic for foreign passenger vessels carrying U.S. passengers or embarking passengers in a U.S. port, as it requires both the vessel's Administration and the Coast Guard to agree that a lifeboat color deviating from International Orange or Vivid Reddish Orange is a comparably highly visible color that will assist detection at sea – and thus complies with LSA Code and SOLAS requirements.

Miami, FL and Port Canaveral, FL hold the titles of largest cruise ports in the world, receiving a combined 8.4 million passengers annually (Mambra, 2022). Throughout the United States, 14.2 million passengers cruised in 2019 (CLIA, 2019). As such, foreign passenger vessels that have obtained acceptance to use alternative lifeboat colors from their flag state and intend to carry U.S. passengers or embark passengers in a U.S. port must also seek approval by the USCG to ensure agreement of compliance with the LSA Code and SOLAS. Failure to obtain USCG approval risks the initiation of a formal intervention preventing the vessel from departing port with passengers, or possibly departing at all (46 USC § 3505, 2021). Consequently, the issuance of MSC.1/Circ. 1423 marked the start of a growing number of case-by-case requests to the Coast Guard for approval of alternative exterior lifeboat colors by IMO Member Governments and/or their designated Administrations.

Simultaneously, the domestic commercial maritime industry began requesting additional colors for USCG-approved lifesaving equipment. While the IMO's interpretation of acceptable lifeboat exterior colors may have influenced this movement, a WorkSafeBC[1]-funded research study published around the same time determined Fluorescent Green – followed by Fluorescent Orange – to be the most conspicuous color for a floating object (henceforth used interchangeably with *target*) in a marine environment (Uglene & Tahermaram, 2011). Fluorescent Pink, sometimes used by the commercial fishing industry for longline, fish trap or crab pot marker buoys has also been suggested. A common argument accompanying requests for acceptance of alternative colors is the age of the potentially outdated U.S. Navy (USN) study that supported

[1] WorkSafeBC is an independent provincial agency dedicated to promoting safe and healthy workplaces across British Columbia (B.C), Canada. They are an exclusive workers insurance provider and all employers in B.C. are required to carry WorkSafeBC coverage unless they are exempt (WorkSafeBC, 2023).

the U.S., SOLAS, and LSA Code lifesaving equipment color requirements. Several IMO Member Governments and maritime industry personnel have expressed opinions that the 1955 study is archaic.

The Lifesaving and Fire Safety Branch (CG-ENG-4) in the Office of Design and Engineering Standards (CG-ENG) at CG Headquarters is the approving authority for lifesaving equipment. Title 46 CFR Subchapter Q contains strict prescriptive and performance requirements to which equipment must be manufactured and independently tested prior to receiving Coast Guard approval; among these requirements is color. Currently, colors permitted for CG-approved lifesaving equipment by Subchapter Q are variations of orange and red: Indian Orange, International Orange, Scarlet Munsell 7.5 Red 6/10, and Vivid Reddish Orange (or a fluorescent color of similar hue). The sole exception is life ring buoys, which may be White on vessels on a domestic voyage only (Lifesaving Equipment, 2021).

1.2 Project Description

The Coast Guard has committed to ensuring that any lifesaving equipment colors differing from those specified by the CFR, SOLAS, LSA Code, or accepted by the USCG prior to the issuance of MSC.1/Circ. 1423, provide a level of safety equal to or exceeding the previously approved hues of orange. To that end, CG-ENG-4 sponsored the RDC Project 1032: *Evaluate Visibility of Colors for CG Approved Lifesaving Equipment in Marine Conditions* to verify or determine the optimal color(s)[2] for CG-approved lifesaving equipment (Figure 2). This literature review is the first product of that project. Terminology used throughout this review is defined in 8APPENDIX A.

Figure 2. Project planning image for Project 1032.

[2] For this report, proper color names are capitalized while general color regimes or hues are presented in lowercase. For example, colors that are defined by color coordinates that fall within the boundaries of a polygon inscribed within a CIE color space (or another recognized method of quantification) are capitalized (e.g., Fluorescent Orange, Yellow). Qualitative color descriptions appear in lowercase letters (e.g., green, blue).

The knowledge gained from this literature review will inform future experiment test plan development by providing guidance on target color selection, the anticipated psychophysical perceptions of test subjects conducting visual search, and recommendations for future research. Once colors are selected and an experiment test plan is approved, the project will conduct field tests to determine the optimally detectable color(s) in the maritime environment under a variety of lighting, weather, and background scene characteristics. The data and associated analysis obtained from field tests will be provided to CG-ENG-4 to inform future CG lifesaving equipment regulation and policy reviews and will be made available to global stakeholders.

1.3 Overview of Color Science

1.3.1 Visible Light and Color Vision

Energy emitted by the sun is composed of electromagnetic waves emitted across a broad spectrum of energy, frequencies, and wavelengths (Figure 3) called the electromagnetic spectrum (Encyclopaedia Britannica [n.d.], 2023).

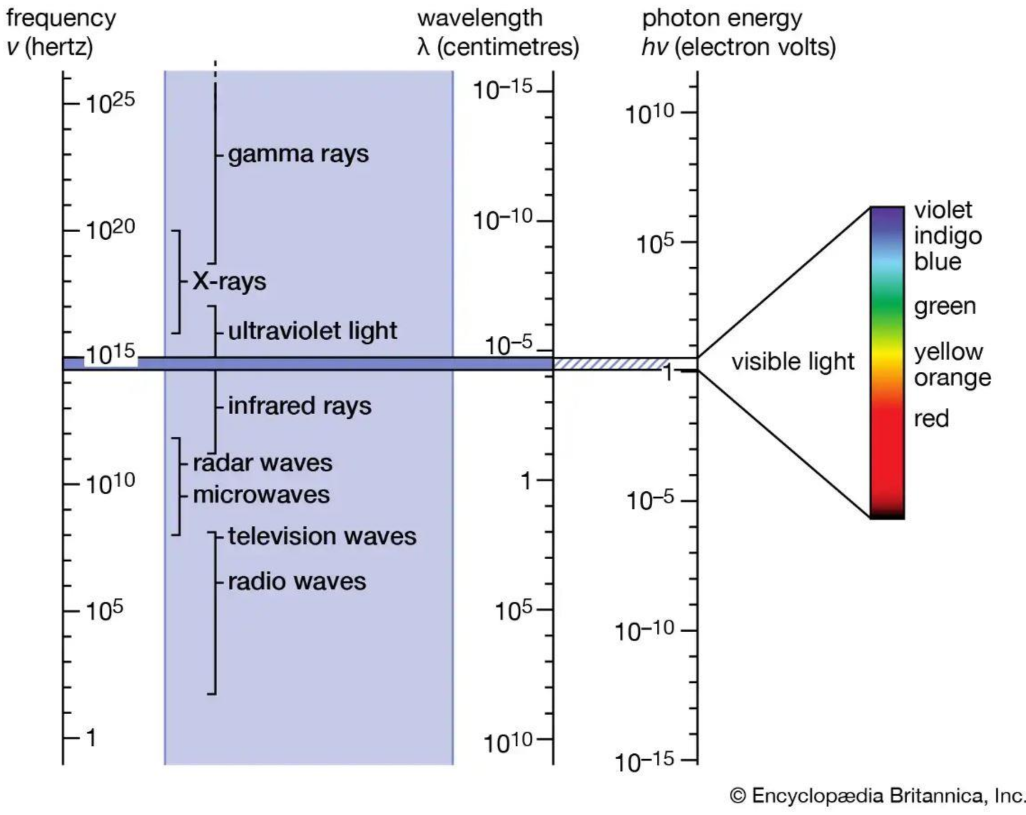

Figure 3. The electromagnetic spectrum (Encyclopaedia Brittanica, 2023).

The range of wavelengths detectable by the human eye is called the visible spectrum and spans approximately 400 nanometers (nm) to 760 nm (Figure 4), though the actual visible range may vary slightly among individuals. Wavelengths of 400 nm and less are in the ultraviolet spectrum, and wavelengths of 760 nm and greater are in the infrared spectrum (Davson, 1980).

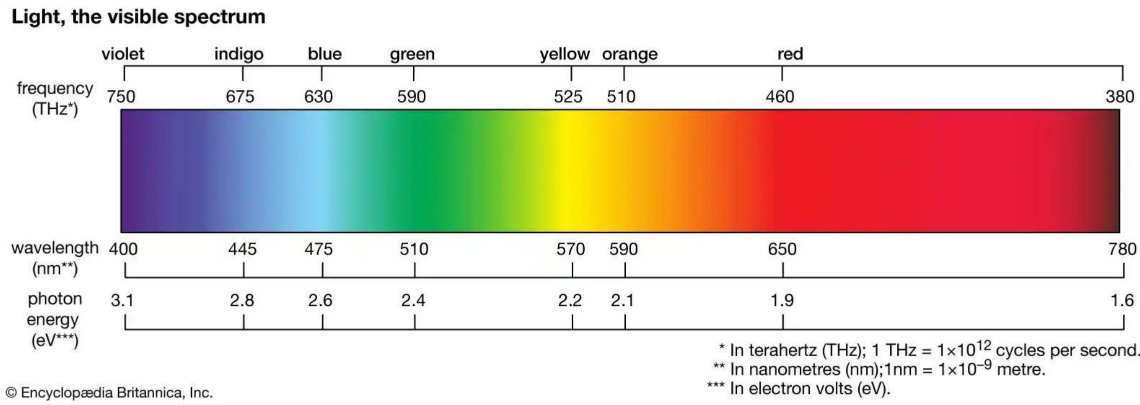

Figure 4. Visible spectrum of light (Encyclopaedia Britannica, 2023).

The human eye is a complex structure, and the physiology of the eye remains a prevalent topic of medical and vision research. Visual phenomena can be divided into three categories: the ability to sense light, color, and form (i.e., to discern shapes or physical characteristics) (Davson, 1980). The ability to sense light and color is dependent on photosensitive rods and cones, which become active under specific lighting conditions.

Rods are highly sensitive to light, and rod activity dominates in low luminance, or *scotopic* conditions. Scotopic vision is characterized by achromaticity and low visual acuity as well as increased reliance on peripheral vision. During high luminance, or *photopic* conditions, rods deactivate (possibly due to over-stimulation) and cone activity dominates. Photopic vision is characterized by full color vision and high visual acuity within direct line of sight (i.e., central vision) that decreases peripheral vision. The range of luminance where some proportion of both rods and cones are active is called mesopic vision (Davson, 1980).

The solid line in Figure 5 is the original photopic curve produced in the 1930s by Jainski (1938), while the dashed line reflects the modern photopic sensitivity curve adopted by the International Commission on Illumination (CIE). The CIE curve displays a maximum photopic stimulus at 555 nm which corresponds to a yellow-green color (Davson, 1980). In short, light at 555 nm generates the greatest photopic response resulting in the greatest visual color stimulus when compared to other wavelengths in the visible spectrum.

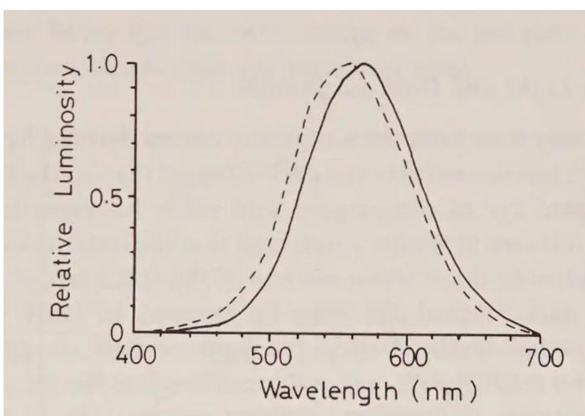

Figure 5. Photopic sensitivity curve (Davson, 1980).

1.3.2 Color Spaces

A color space is a system that mathematically describes the way colors are represented. It is an abstract model that maps colors onto a three-dimensional coordinate system, allowing for accurate color representation and manipulation. Color spaces are used in colorimetry to describe the color characteristics of a specific medium such as a digital display, a printed photo, or human vision. The choice of color space is critical for ensuring that colors are accurately represented and reproduced across different devices and mediums (Fairchild, 2005).

Common color spaces include RGB, CMYK, CIE XYZ, and CIELAB (also referred to as CIE L*a*b). The RGB color space (based on red, green, and blue) is a color space typically used in digital imaging and monitors, whereas CMYK (based on cyan, magenta, yellow, and key [i.e., black)]) is most often applied in printing applications (Fairchild, 2005). CIE XYZ is a color space defined by the CIE and serves as a standardization reference space for all other color spaces. It is a device-independent color space and is not tied to a specific medium (CIE, 2004). CIELAB is a perceptual color space that models human vision and is often used for color identification, matching, and correction (Fairchild, 2005). For this reason, CIELAB is the color space preferred in most color perception and vision research applications. CIELAB uses the term a^* to specify a distance within the color space along the green and red axis, and the term b^* to specify a distance along the blue and yellow axis. The term L^* is a measure of luminance (perceived lightness) and is used to specify a distance along the black and white axis (Figure 6).

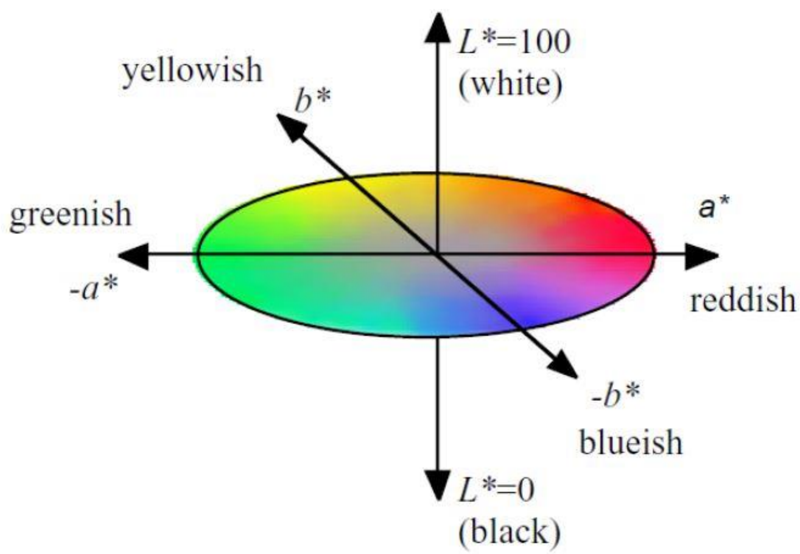

Figure 6. Illustration of CIELAB color space (Andersen, 2013).

Color spaces require a white point to accurately depict colors. The white point is a reference for color space calibration and corresponds to an achromatic white stimulus under specified lighting conditions. For example, the chromaticity coordinates of achromatic white differ in natural daylight as compared to artificial light (Ohta & Robertson, 2005). The CIE has standardized white points for various illumination sources; the white point for natural sunlight is CIE standard illuminant D65 (CIE, 2004). For daytime visual search, CIE standard illuminant D65 is the preferred white point for color space calibration.

1.3.3 Conspicuity and Detectability

Conspicuity is the culmination of properties or characteristics of an object that increase the likelihood that it will draw the attention of an observer (ANSI/ISEA, 2020). An object's degree of conspicuity can vary with environmental factors such as light and weather conditions, background color, and the complexity of the search location. Conspicuity and hence, detectability can likely be increased by maximizing chromaticity and luminance differences from the object's background (ANSI/ISEA, 2020).

1.3.4 Chromaticity and Luminance

Chromaticity is the color of an object as defined by chromaticity coordinates, independent of its luminance (IALA [n.d.], 2023). Luminance is a measurable quantity most closely associated to the human psychophysical perception of brightness (ASTM International, 2000), often referred to as perceptual lightness (CIE, 2004). As discussed in section 1.3.2, CIELAB is the preferred color space for the human perception of color and incorporates both luminance (L^*) and color coordinates (a^* and b^*).

2 U.S. REGULATIONS AND INTERNATIONAL CONVENTIONS

2.1 U.S. Regulatory Review of CG-Approved Lifesaving Equipment Colors

Title 46 CFR Subchapter Q references three standards for lifesaving equipment color requirements: the *Standard Color Card of America* (SCCA) published by the Color Association of the United States; the National Bureau of Standards (NBS) *Color Names Dictionary*; and FED-STD-595 – *Colors Used in Government Procurement*. In 1976 the *Color Names Dictionary* was combined with NBS *Universal Color Language* and renamed NBS Special Publication 440 – *Color – Universal Language and Dictionary of Names* (Kelly & Judd, 1976). In 2017 FED-STD-595 was superseded by AMS-STD-595 – *Colors Used in Government Procurement*, and the original CIE XYZ tristimulus values contained in FED-STD-595 were updated to CIELAB color coordinates (SAE International, 2017).

The specifications for CG-approved equipment are contained in 46 CFR Subchapter Q – *Equipment, Construction, and Materials: Specification and Approval*. Subchapter Q spans 46 CFR §156 – 165; the lifesaving equipment specifications and approval requirements are contained in 46 CFR §160 – *Lifesaving Equipment*. A summary of CG-approved lifesaving equipment color requirements listed in 46 CFR §160 is summarized in Table 1.

Table 1. Summary of CG-approved lifesaving equipment colors.

Cite	Equipment	Color(s)	Color Reference
46 CFR 160.001-2(h)	Life Preservers – General	Indian Orange International Orange Scarlet Munsell Red	Self-referenced
46 CFR 160.002-3(b)	Life Preservers – Kapok	Indian Orange Scarlet Munsell 7.5 Red 6/10	SCCA
46 CFR 160.005-3(b)	Life Preservers – Fibrous Glass	Indian Orange Scarlet Munsell 7.5 Red 6/10	SCCA
46 CFR 160.010-3(a)	Inflatable Buoyant Apparatus	Vivid Reddish Orange [a]	FED-STD-595
46 CFR 160.010-4(n)	Buoyant Apparatus	Vivid Reddish Orange	FED-STD-595
46 CFR 160.027-2(a)	Life Floats	Vivid Reddish Orange	FED-STD-595

Table 1. Summary of CG-approved lifesaving equipment colors (Cont'd).

Cite	Equipment	Color(s)	Color Reference
46 CFR 160.050-3(b)	Life Ring Buoys	International Orange White (domestic routes only)	FED-STD-595
46 CFR 160.051-7	Inflatable Liferafts – Domestic Service (Coastal)	Vivid Reddish Orange [a]	FED-STD-595
46 CFR 160.051-9	A and B Inflatable Liferafts – Domestic Service (Coastal)	Vivid Reddish Orange [a]	FED-STD-595
46 CFR 160.053-3	Work Vests	Indian Orange Scarlet Munsell 7.5 Red 6/10	SCCA
46 CFR 160.055-3(c)	Standard Life Preservers – Unicellular Plastic Foam (Envelope)	Indian Orange Scarlet Munsell 7.5 Red 6/10	SCCA
46 CFR 160.055-3(j)	Standard Life Preservers – Unicellular Plastic Foam (Vinyl Coating)	International Orange Scarlet Munsell 7.5 Red 6/10	SCCA
46 CFR 160.055-4	Nonstandard Life Preservers – Unicellular Plastic Foam (Envelope)	Indian Orange Scarlet Munsell 7.5 Red 6/10	SCCA
46 CFR 160.055-4	Nonstandard Life Preservers – Unicellular Plastic Foam (Vinyl Coating)	International Orange Scarlet Munsell 7.5 Red 6/10	FED-STD-595
46 CFR 160.055-5(b)(2)	Standard Life Preservers – Unicellular Plastic Foam (Vinyl Coating)	International Orange Scarlet Munsell 7.5 Red 6/10	FED-STD-595
46 CFR 160.055-6(a)	Nonstandard Life Preservers – Unicellular Plastic Foam (Vinyl Coating)	International Orange Scarlet Munsell 7.5 Red 6/10	FED-STD-595
46 CFR 160.076-23(a)(1)	Inflatable Work Vests	Orange Vivid Reddish Orange	NBS
46 CFR 160.077-17(b)(3)	Type 1 Hybrid PFDs	Vivid Reddish Orange	NBS
46 CFR 160.135-7(b)(24)	Lifeboats	Vivid Reddish Orange [a]	FED-STD-595
46 CFR 160.151-15(e)	Inflatable Liferafts (SOLAS)	Vivid Reddish Orange [a]	FED-STD-595
46 CFR 160.151-17	A and B Inflatable Liferafts (SOLAS)	Vivid Reddish Orange [a]	FED-STD-595
46 CFR 160.156-7(a)(6)	Rescue Boats and Fast Rescue Boats (SOLAS)	Vivid Reddish Orange [a]	FED-STD-595
46 CFR 160.171-9(h)	Immersion Suits	Vivid Reddish Orange	NBS
46 CFR 160.174-9(f)	Thermal Protective Aids	Vivid Reddish Orange	NBS
46 CFR 160.176-9(a)(10)	Inflatable Lifejackets	Vivid Reddish Orange	NBS

[a] or a fluorescent color of similar hue.

Approved colors for lifesaving equipment listed in 46 CFR §160 are Indian Orange, International Orange, Scarlet Munsell 7.5 Red 6/10, and Vivid Reddish Orange. Also included are standard Orange for inflatable work vests, and White for life ring buoys on vessels on domestic voyages. Both Orange work vests and White life ring buoys are intended for use near shore or in protected waters, where a greater emphasis lies in keeping the user afloat versus enhancing visual detection of the user in potentially adverse conditions. Conversely, domestic regulations do not prescribe color requirements for recreational lifesaving equipment.

2.2 International Conventions and Interpretations of Lifesaving Equipment Colors

2.2.1 International Convention for the Safety of Life at Sea

The International Convention for the Safety of Life at Sea (SOLAS) is an international treaty formed to increase the safety of ships by establishing minimum standards for construction, equipment, and operations (IMO, 2023). SOLAS Chapter III discusses lifesaving appliances and arrangements. SOLAS Chapter III, Regulation 34 (formatted as SOLAS III/34 henceforth) requires all lifesaving equipment to comply with the International Life-Saving Appliance (LSA) Code (IMO, 2023). The LSA Code color requirements are similar to U.S. federal regulations, citing two specific colors as acceptable for lifesaving equipment. International Orange and Vivid Reddish Orange are the only colors permitted by the SOLAS Convention and LSA Code. A vessel's Administration may also approve "a comparably highly visible color", which is left to the interpretation of each Administration. A truncated summary of lifesaving equipment color requirements is included below; caveats that replicate color requirements for the same equipment have been omitted (Table 2.Table 2).

Table 2. Summary of SOLAS-approved lifesaving equipment colors.

Cite	Equipment	Color(s)	Color Reference
SOLAS III/7.1.1	Lifebuoys - General	International Orange [a] Vivid Reddish Orange [a]	LSA Code 2.1.1
SOLAS III/7.2.1	Lifejackets - General	Same as above	LSA Code 2.2.1 and 2.2.2
SOLAS III/7.3	Immersion Suits - General	Same as above	LSA Code 2.3
SOLAS III/7.3	Anti-exposure Suits - General	Same as above	LSA Code 2.4
SOLAS III/21.1.1.1	Lifeboats - Passenger ships	Same as above	LSA Code 4.5 and 4.6
SOLAS III/21.1.1.2	Liferafts - Passenger ships	Same as above	LSA Code 4.2 and 4.3
SOLAS III/21.1.5	Marine Evacuation System - Passenger ships	Same as above	LSA Code 6.2.3.1
SOLAS III/21.2.1	Rescue Boats - Passenger ships	Same as above	LSA Code 5.1
SOLAS III/22.2.1	Lifejackets - Passenger ships	Same as above	LSA Code 2.2.1 and 2.2.2
SOLAS III/22.4.1	Immersion Suits - Passenger ships	Same as above	LSA Code 2.3
SOLAS III/22.4.1	Thermal Protective Aids - Passenger ships	Same as above	LSA Code 2.5
SOLAS III/26.3.1	Fast Rescue Boats - Ro-Ro Passenger ships	Same as above	LSA Code 5.1.4
SOLAS III/31.1.1.1	Totally Enclosed Lifeboats - Cargo ships	Same as above	LSA Code 4.6
SOLAS III/31.1.1.2	Liferafts - Cargo ships	Same as above	LSA Code 4.2 and 4.3
SOLAS III/31.1.2.1	Free-fall Lifeboats - Cargo ships	Same as above	LSA Code 4.7
SOLAS III/31.1.3.3	Totally Enclosed Lifeboats - Cargo ships	Same as above	LSA Code 4.6
SOLAS III/31.1.4	Liferaft - Cargo ships	Same as above	LSA Code 4.2 and 4.3
SOLAS III/31.1.6	Lifeboat with self-contained air support system - Cargo ships	Same as above	LSA Code 4.8
SOLAS III/31.1.7	Fire-protected Lifeboats - Cargo ships	Same as above	LSA Code 4.9
SOLAS III/31.2	Rescue Boats - Cargo ships	Same as above	LSA Code 5.1
SOLAS III/31.3.2	Liferaft - Cargo ships	Same as above	LSA Code 4.2 and 4.3
SOLAS III/32.1.1	Lifebuoys - Cargo ships	Same as above	LSA Code 2.1
SOLAS III/32.3.2	Immersion Suits - Cargo ships	Same as above	LSA Code 2.3

[a] or a comparably highly visible color

2.2.2 International Association of Classification Societies

The International Association of Classification Societies (IACS) is a nonprofit organization of classification societies and the principal technical advisor to the IMO (IACS, 2023). IACS develops minimum technical requirements and assists international regulatory bodies and standards organizations to develop, implement, and interpret regulations and industry standards for the design, construction, and maintenance of ships (IACS, 2023). The 11 members of IACS are: the American Bureau of Shipping; Bureau Veritas; China Classification Society; Croatian Register of Shipping; Det Norske Veritas; Indian Register of Shipping; Korean Register; Lloyds Register; ClassNK; Polish Register of Shipping; and RINA S.p.A. (IACS, 2023).

IACS issues Unified Interpretations (UI) to ensure consistency in the application of international regulations by member organizations. UI SC233, *LSA Code – lifeboat exterior colour* is currently the only UI explicit to lifesaving equipment colors. The UI provides an interpretation of LSA Code 1.2.2.6 (lifesaving equipment colors), clarifying that "highly visible colour only includes colours of strong chromatic content, i.e., pure achromatic colours such as white and all shades of grey shall not be accepted as 'comparable' colours" (IACS, 2012). Identical to the SOLAS Convention described in Section 2.2.1, a "comparably highly visible color" is left to the interpretation of each IACS member Administration.

3 INDUSTRY STANDARDS

3.1 Marine and Aeronautical Lifesaving Equipment Standards

Unlike laws or regulations, *standards* are not mandatory unless an enforcement body incorporates them into regulation. Federal agencies including the USCG, Federal Aviation Administration, Occupational Safety and Health Administration and many others have incorporated by reference numerous standards into the CFR. Standards are typically produced by professional societies or industry organizations and often cited as best practices. There are several industry standards that address lifesaving equipment colors. While standards differentiate between recreational lifesaving equipment and commercial lifesaving equipment, the primary goal is conspicuity for detection. For that reason, industry standards pertaining to color recommendations – regardless of intended use – have been included in this document. A summary of relevant standards and respective colors are provided in Table 3.

Table 3. Summary of marine lifesaving equipment industry standards color recommendations.

Organization	Standard	Color(s)
International Organization for Standardization	ISO 12402-7: Personal Flotation Devices – Part 7: Material & Components Safety Requirements & Test Methods	Yellow Orange Red Fluorescent Yellow Fluorescent Yellow-Orange Fluorescent Orange Fluorescent Orange-Red Fluorescent Red
SAE International [a]	AS1354: Individual Inflatable Life Preserver [b]	International Orange-Yellow
SAE International [a]	AS1356: Life Rafts [b]	International Orange-Yellow
UL Solutions	UL 1123: Standard for Marine Buoyant Devices	International Orange Scarlet Munsell 7.5 Red 6/10 Indian Orange
UL Solutions	UL 1180: Standard for Safety – Fully Inflatable Recreational Personal Flotation Devices	Orange Vivid Reddish Orange
UL Solutions	UL 1191: Standard for Components for Personal Flotation Devices	Yellow Orange Red Fluorescent Yellow Fluorescent Yellow-Orange Fluorescent Orange Fluorescent Orange-Red Fluorescent Red
UL Solutions	UL 1197: Standard for Immersion Suits	Vivid Reddish Orange
UL Solutions	UL 1517: Standard for Hybrid Personal Flotation Devices	Vivid Reddish Orange
American National Standards Institute UL Solutions Standards Council of Canada	ANSI/CAN/UL 12402-4: Standard for Safety – Personal Flotation Devices – Part 4: Lifejackets, Performance Level 100 – Safety Requirements	Fluorescent Yellow-Orange Fluorescent Red-Orange
American National Standards Institute UL Solutions Standards Council of Canada	ANSI/CAN/UL 12402-9: Standard for Safety – Personal Flotation Devices – Part 9: Test Methods	Yellow Orange Red Fluorescent Yellow Fluorescent Yellow-Orange Fluorescent Orange Fluorescent Orange-Red Fluorescent Red

[a] widely associated with the motor vehicle industry; however, SAE also produces aerospace standards

[b] denotes an aerospace standard

While hues of orange and red dominate U.S. domestic and international regulations, standards organizations include a broader range of colors. Many standards are intended to apply to recreational lifesaving equipment, while others are nondescript in their application, leaving the determination to regulatory authorities. In addition to the hues of orange previously discussed, industry standards also include hues of yellow, orange, and red. Fluorescent hues in that same color range are also integrated into the standards. The

SAE International documents listed in Table 3 are aerospace standards, and the only standards that reference International Orange-Yellow.

3.2 High Visibility Color Standards

High Visibility Safety Apparel (HVSA) color standards were reviewed for worker occupational safety. While not specific to maritime lifesaving equipment, HSVA is "personal protective safety clothing intended to provide conspicuity during both daytime, nighttime, and other low-light conditions" (ANSI/ISEA, 2020). In addition, marking standards for emergency response vehicles were reviewed for potential applicability to lifesaving equipment. The results are contained in Table 4.

Table 4. Summary of high visibility color standards recommendations.

Organization	Standard	Colors(s)
American National Standards Institute	ANSI Z535.1: Safety Colors	Restricted Red [a] Restricted Orange [a] Unrestricted Red-Orange [a] Restricted Yellow [a] Unrestricted Yellow [a] Green [a]
American National Standards Institute International Safety Equipment Association (ISEA)	ANSI/ISEA 107: High Visibility Safety Apparel	Fluorescent Yellow-Green Fluorescent Orange-Red Fluorescent Red
U.S. Department of Transportation (DOT)	MUTCD: Manual on Uniform Traffic Control Devices [b]	Fluorescent Orange-Red [c] Fluorescent Yellow-Green [c]
International Organization for Standardization	ISO 20471: High Visibility Clothing – Test Methods and Requirements	Fluorescent Yellow Fluorescent Orange-Red Fluorescent Red
National Fire Protection Association	NFPA 1901: Standard for Automotive Fire Apparatus [d]	Red [e] Yellow [e] Fluorescent Yellow [e] Fluorescent Yellow-Green [e]

[a] while not stated within the color name, denotes a fluorescent color
[b] many sections contain requirements versus recommendations
[c] or a combination of these colors
[d] the term *automotive fire apparatus* refers to a fire response vehicle (i.e., a fire truck)
[e] to be used in a chevron pattern, alternating between Red and either Yellow, Fluorescent Yellow, or Fluorescent Yellow-Green

In addition to color requirements, the National Fire Protection Association (NFPA) standard 1901 introduces pattern recommendations, notably a chevron (Figure 7. NFPA 1901-compliant chevron markings for fire emergency vehiclessee Figure 7) with alternating colors (FAMA, 2023).

Figure 7. NFPA 1901-compliant chevron markings for fire emergency vehicles (FAMA, 2023).

4 PREVIOUS LIFESAVING EQUIPMENT COLOR-RELATED WORK

The Testing and Development Division (now the CG Research, Development, Test & Evaluation Program) at CG Headquarters conducted the earliest documented Coast Guard color study. It found that White life jackets and Indian Orange life jackets were equally visible in daylight with no whitecaps present. In daylight with whitecaps present, the Indian Orange life jacket was seen at nearly double the distance as the White life jacket (Creedon, 1948).

Halsey et al. (1955) of the USN Medical Research Laboratory conducted a comprehensive study to determine the detectability of various colors in the maritime environment in support of at-sea and air-sea search and rescue. Eighteen standard colors and four fluorescent colors were tested in Long Island Sound, between the Connecticut and Long Island, New York shorelines. They deployed 0.86 meter (m) (2.8 feet [ft]) diameter floating metal spheres, three sizes of life rafts ranging from 1.6 m (4.5 ft) to 3.7 m (12 ft) in length, and a dummy outfitted with a life jacket and aviator's helmet. An aircraft maintained 296 kilometers per hour (160 knots) at an altitude of 213 m (700 ft) while four observers searched for targets. Each observer recorded the time at which they detected a target and its perceived color. When the aircraft was directly over the target (the closest approach distance), the observers again recorded the time and perceived target color. These data were used to derive target detection distance, as well as record correct color identification and any perceived color variation with distance. All field testing took place between mid-morning and mid-afternoon in fair weather conditions, as aircraft and water-based support vessel operations were constrained by visibility and sea state.

The USN study found that common characteristics of highly detectable targets were high chromaticity, high luminosity, or a combination of both. The background color (i.e., the water color, as viewed from the aircraft) during each trial had a significant impact on the detectability of individual colors. When the water appeared darker due to weather and light conditions, lighter colored (i.e., higher luminosity) targets such as whites and yellows were detected at a greater distance; when the water appeared lighter, darker saturated color targets such as oranges and reds prevailed. Hence, greater contrasts between target color and background color resulted in increased detection distances. Additionally, yellow hues (including Fluorescent Yellow) were often misidentified as White at longer distances. While white and yellow hued targets were highly detectable in many trials that took place under optimum environmental conditions, the study concluded these colors may be mistaken for white caps, sea gulls, or flotsam in a SAR operational environment. Lastly, while the four fluorescent colors tested exhibited superior detectability during field testing, commercially available fluorescent dyes were relatively new and prone to color instability, which the researchers identified as a concern (Halsey et al., 1955).

In 2017, Federal Standard (FED-STD) 595, *Colors Used in Government Procurement* (incorporated by reference into the CFR) was cancelled, temporarily invalidating the Coast Guard's regulatorily incorporated reference for lifesaving equipment colors. In 2018 CG-ENG-4 contracted UL Solutions (UL) to determine whether the CIE color coordinates corresponding to CG-approved hues of orange fell within the color coordinates specified in International Organization for Standardization (ISO) 12402-7 – *Personal Flotation Devices – Part 7: Materials and Components – Safety Requirements and Test Methods* for those same colors. This analysis was performed to inform the CG Commercial Regulations & Standards Directorate (CG-5PS) whether ISO 12402-7's color definitions encompassed CG-approved lifesaving equipment colors, thereby serving as a potential color reference. UL Solutions determined from material and equipment samples, as well as color cards, that CG-approved lifesaving equipment colors do fall within the CIE color coordinates contained in ISO 12402-7 Tables 3 and 4 (UL Solutions, 2019). The study also defined the CIE color coordinate limits of CG-approved lifesaving equipment by describing a polygon within CIE color space (Figure 8).

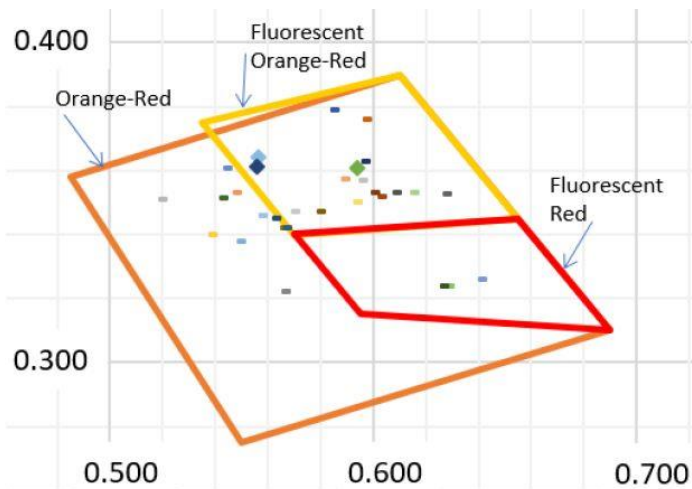

Figure 8. Example of CIE coordinates for CG-approved lifesaving equipment colors compared to ISO 12402-7 color-defined polygons (UL Solutions, 2019).

While FED-STD-595 was eventually replaced by SAE International standard AMS-STD-595, *Colors Used in Government Procurement*, the study quantitatively defined CG-approved lifesaving equipment colors. It also identified areas of potential future research such as obtaining luminosity data and the effect of materials and material substrate on color presentation and color stability.

The USCG and Transport Canada participated in the development of UL 12402-5 – *Personal Flotation Devices – Part 5: Buoyancy Aids (Level 50) – Safety Requirements* and UL 12402-9 – *Personal Flotation Devices – Part 9: Test Methods*. These new UL standards were created to replace (in part) legacy standards UL 1123 – *Marine Buoyant Devices*, UL 1180 – *Fully Inflatable Recreational Personal Flotation Devices*, and UL 1517 – *Hybrid Personal Flotation Devices*, creating a common North American personal flotation device (PFD) standard (CG-ENG, 2018). Following the promulgation of these standards, CG-ENG issued policy letter 02-18 in August of 2018 accepting Level 70 PFDs complying with UL 12402-5 and tested to UL 12402-9 as equivalent to wearable PFD requirements contained in 46 CFR §160.064 – *Marine Buoyant*

Devices, 46 CFR §160.076 – *Inflatable Recreational Personal Flotation Devices*, or 46 CFR §160.077-15 – *Construction and Performance – Recreational Hybrid PFD*. This policy does not include infant wearable PFDs, throwable PFDs, work vests, or lifesaving devices required for U.S.-flagged inspected vessels, uninspected passenger vessels, and uninspected commercial vessels under 12 m (40 ft) (CG-ENG, 2018). This policy letter and referenced CFR sections pertain to recreational lifesaving equipment only.

Worcester Polytechnic Institute (WPI) undergraduate students initiated an Interactive Qualifying Project (a graduation fulfillment requirement) sponsored by CG-ENG-4 in 2020 titled *Reevaluating the Colors of USCG Life Saving Equipment* (Angel et al., 2020). This study provided background on human vision and visual search, and concluded by developing a comprehensive experimental test plan to evaluate nine colors in a variety of lighting, sea state, and weather conditions. Execution of the test plan was beyond the scope of the project; however, the literature review and personnel interviews provided a solid foundation for future work. The WPI project was the precursor to this RDC project.

5 LITERATURE REVIEW

5.1 Color Studies

There is a decided lack of research on color conspicuity in the maritime environment. Several USN Medical Research Laboratory color studies preceded Halsey et al. (1955) but few have followed, likely due to the comprehensive scope of the Halsey et al. report. Highway, rail, and forestry-related color conspicuity research dominates the research field; however, many of the findings are insightful and generalize beyond the search environment.

The International Association of Marine Aids to Navigation and Lighthouse Authorities (IALA) has published many standards and guidance documents for aids to navigation color requirements, primarily for color standardization for various aids. However, IALA G1094 – *Daymarks for Aids to Navigation* includes brief discussions on color patterns (discussed further in Section 5.1.4), color variation at distance, and luminous and background contrast with associated calcuations. While these calculations are useful, the user must input information that varies by atmospheric, weather, lighting, and seasonal conditions including luminance of the object, luminance of the background, and atmospheric extinction coefficients.

5.1.1 Maritime Color Studies

Halsey et al. (1955) published a thorough report comparing 22 distinct colors, concluding the detectibility of Fluorescent Yellow-Orange and Fluorescent Red-Orange far exceeded standard (i.e., non-fluorescent) colors. They also found high saturation and/or high brightness colors performed best among standard colors, with the exception of Yellow and White. Uglene and Tahermaram (2011) observed Fluorescent Green (perceptually a fluorescent yellow-green hue) followed by Fluorescent Orange targets were most detectable during on-water testing compared to standard Yellow and standard Red targets. Interestingly, Uglene and Tahermaram's test environment was generally overcast which may have provided greater contrast for higher luminance colors.

5.1.2 Terrestrial Color Studies

The University of Michigan's Transportation Research Institute conducted numerous studies on pedestrian color conspicuity by varying garment colors, ambient lighting (e.g., low light, bright light, etc.), and environment background (e.g., seasonal foliage). In field trials evaluating Fluorescent Red-Orange and

Fluorescent Yellow-Green, only scene complexity affected detection distance (Sayer & Mefford, 2005). When tested at civil twilight, Sayer and Meffor (2006) found no statistical difference in conspicuity between Fluorescent Red-Orange and Fluorescent Yellow-Green. Buonarosa and Sayer (2007) investigated seasonal background differences (summer versus fall), and concluded that Fluorescent Red-Orange and Fluorescent Yellow-Green were equally conspicuous. Buonarosa and Sayer also suggested the detectibility of Fluorescent Red-Orange may be due to color contrast with the naturalistic environment, while the detectibility of Fluorescent Yellow-Green may be due to luminance contrast; this mirrors the discussion of Halsey et al. (1955). Zwahlen and Vel (1994) examined 10 colors for highway safety and recommended Fluorescent Yellow and Fluorescent Orange for use on all traffic control devices and signs. Similarly, Turner et al. (1997) tested eleven colors for daytime highway roadwork use and found Fluorescent Red-Orange was most conspicuous followed by Fluorescent Red, Fluorescent Yellow-Green, and a Fluorescent Red-Orange/Fluorescent Yellow-Green combination. Six safety colors tested for forestry workers by Isler et al. (1997) found that White, Fluorescent Lime-Yellow, and Fluorescent Orange, respectively, were most conspicuous in a New Zealand pine forest. Killeen (2005) while studying emergency vehicle colors claimed the human eye is most drawn to Green-Yellow due to the high luminosity of its yellow hues and chromaticity contrast with most natural colors. Therefore, color conspicuity is influenced by inherent color and luminance contrast properities in figure-background (i.e., target-environment) pairings.

5.1.3 Fluorescent versus Standard (Non-fluorescent) Colors

Schieber et al. (2006) observed that fluorescent colors automatically attracted visual attention even when unrelated to the goal target color. The U.S. Fire Administration (2009) conducted an emergency vehicle conspicuity study and concluded that fluorescent colors, in particular Fluorescent Yellow-Green and Fluorescent Orange, present better detectability during daylight hours compared to nonfluorescent colors tested. Fluorescent Orange signs substituted for standard Orange work zone signs were recognized more accurately and at greater distances by Hawkins et al. (1998). When standard Yellow warning signs were replaced with Fluorescent Yellow signs at hazardous intersections, a measurable increase in safety was seen (Krull, 2000). Overall, fluorescent colors have consistently out performed standard colors in the tested environments.

5.1.4 Color Patterns

Color patterns have been observed to promote conspicuity. The IALA suggests the use of stripes or geometric patterns of high conspicuity color combinations to increase the detectability of aids to navigation (IALA, 2016). Sayer and Mefford (2000) found that while Fluorescent Orange and Fluorescent Yellow fabrics performed well individually, garments containing both colors performed exceptionally well. The Manual on Uniform Traffic Control Devices (MUTCD) for Streets and Highways calls out patterns for traffic barriers (Federal Highway Administration, 2009). The U.S. Fire Administration (2009) Emergency Vehicle Visibility and Conspicuity Study analyzed various patterns from the U.S. and abroad; while not identifying a “best use” pattern, they did acknowledge patterns employing high luminance and high color contrasts are likely to be most conspicuous. This statement is reflected in National Fire Protection Association (NFPA) standard 1901, which identifies a 45° downward-pointing chevron of alternating Red and either Yellow, Fluorescent Yellow, or Fluorescent Yellow-Green stripes (NFPA, 2016). While researching high visibility objects in a sunset environment, Iizuka et al. (2021) determined that alternating diagonal stripes of Black and Yellow (25% black, 75% yellow overall area) angled at 165° resulted in the highest detectibility.

5.2 Visual Search

A key challenge in human information processing is the vast amount of sensory information constantly being taken in by our sensory organs (i.e., photoreceptors, auditory hair cells, etc.). The problem is that humans cannot fully process all the sensory data and require selective attention to focus the processing of relevant information while suppressing irrelevant information; see Driver (2001) for a historical review. Research with visual search paradigms have been conducted for years to better understand selective attention and search guidance in a variety of environments. To evaluate optimally detectable colors for lifesaving equipment in the marine environment, the intricacies of visual search must also be examined (i.e., what makes a search object more detectable?).

Treisman and Gelade (1980) described in their influential Feature Integration Theory two-stages of visual processing: preattentive and attentive stages. The preattentive stage processes basic visual features such as color and orientation in parallel across the visual field. This processing occurs by cortical cells and areas specialized to process specific features (Zeki, 1978). The attentive stage requires selective attention to *bind* features together (e.g., color and size) in a single representation. The attentive stage is capacity limited such that attending to, and binding features, happens through a serial process of one or a few items, then moves to different items.

Wolfe et al. (1989) proposed in his Guided Search Theory that basic visual features can guide selective attention to the target of a visual search with more or less efficiency. Wolfe (2021), now in his 6th model of Guided Search (i.e., Guided Search 6.0), claims visual search guidance comes from five types of preattentive information: bottom-up, top-down, prior history, value, and scene guidance. These sources of attentional guidance are described separately, but they are complexly intertwined in visual search scenarios (Awh et al., 2012; Wolfe, 2021). For example, if mariners have abandoned ship and boarded a liferaft, a SAR responder's search can be guided by the contrast of the liferaft to its surroundings, specific expected liferaft features (e.g., shape, size, color, etc.), and their prior knowledge and search experience for liferafts in the marine environment. The aim of guidance is to improve search performance, which is often measured in terms of response time[3] and error rates.

5.2.1 Bottom-up Attentional Guidance

Bottom-up attentional guidance is driven by external factors (i.e., stimulus-driven) that capture the observer's attention and is typically associated with the salience of an object in the search environment. Itti and Koch (2001) described salience, in terms of physical salience, as how much the basic, low-level visual features of a stimulus differ from surrounding stimuli (i.e., contrast). The salience of a search target is impacted by several factors such as the contrast between the target and distractors, amongst distractors (Duncan & Humphreys, 1989), as well as the target against ambient background color (Mina et al., 2021). Egeth et al. (1972) noted that when a single feature is unique compared to its surroundings (e.g., one red X amongst black X's), it is a feature singleton, which can *pop out* to an observer. Examples of bottom-up search guidance include a single bright orange lifeboat against a dark blue ocean or the flash of retroreflective material in contrast with a dark night sky. Although these attributes can greatly assist in target detection, Anderson et al. (2015) concluded that highly salient distractors are also likely to capture the attention of a searcher (henceforth used interchangably with *observer*), reducing search efficiency through

[3] *Response time* in visual search literature refers to the elapsed time between presenting a search target and the observer responding to that target. In contrast, the USCG often uses response time to describe the elapsed time between launching search assets and those assets arriving on-scene to begin a search.

momentary distraction. For example, searching for a PIW in the debris field of a capsized boat where a bright white cooler may pop out.

The salience of a search target has a significant impact on detectability. Theeuwes (1994) concluded that object detection was completely dependent on the salient properties of objects within the search field, with the most salient object involuntarily capturing attention. Mina et al. (2021) determined the primary attribute influencing conspicuity during daylight hours is the color contrast between the background environment and the wearer's apparel. Bauer et al. (1998) and Carter (1980) surmised that less color contrast between targets and the search field led to increased search times, while greater color contrast resulted in reduced search times and improved search performance. Tatler et al. (2005) found observers demonstrated eye movement bias toward areas of high luminance contrast and edge density, i.e., the distinctness and number of a target's edges. Through monitoring eye movements, Anderson et al. (2015) determined that high salience objects had a notable influence on oculomotor behavior. Even with a predetermined goal target in mind, immediate, short-term eye movements were directed toward high contrast objects before moving to the goal target.

5.2.2 Top-down Attentional Guidance

Bacon and Egeth (1994) described top-down attentional guidance (i.e., goal-directed) as internal to the observer's search intentions. This guidance originates from the observer's knowledge or beliefs about a given task that guides their search and influences what is selected in their visual field. In opposition to stimulus-driven attentional capture, Folk et al. (1992) put forth their *contingent involuntary orienting hypothesis,* which describes that attentional capture to an object is contingent on the attentional set of the searcher. The attentional set is programmable to control what is attended to by the searcher. Importantly, physical salience alone will not involuntarily capture attention, unless it is congruent with the attentional set.

In terms of visual search, if an observer is searching for a red X amongst black X's, red W's, and a single black O, the observer can improve their search efficiency by entering a *feature search mode* by narrowing their attentional set for red. This would reduce the number of items to-be-searched to only red items, and the unique black O will not involuntarily capture attention (Bacon & Egeth, 1994; Folk et al., 1992). A real-world example is if SAR responders are told that crewmembers from a ship in distress have abandoned ship and are now on an orange liferaft. The SAR responders can establish their *attentional set* to guide search for orange as opposed to other colors in the environment. Importantly, if orange is unique and highly salient, then a *singleton detection mode* may capture attention through stimulus-driven processing of the conspicuity of the orange liferaft, which may be the default search mode. However, a feature search mode may be a more efficient search strategy than a singleton detection mode when other irrelevant singletons are present (Bacon & Egeth, 1994; Anderson et al., 2015).

Specific to color guidance, how many colors can efficiently guide search? Buetti et al. (2019) and Hulleman (2020) posited that color is a guiding feature dimension for object detection, particularly when task-relevant. Wolfe (2007) claims a single feature (e.g., orange, red, blue, etc.) within a dimension (e.g., color) can guide attention in any given moment. For example, a SAR responder's search can be guided by the color orange, but not simultaneously by both orange and green. Prior research on multiple-color visual search by Grubert and Eimer (2013) and Grubert et al. (2016) suggests that single-color guidance is more efficient than multiple-color guidance. Menneer et al. (2019) observed that holding a color in working memory while searching for a second color increased error rates among observers, and theorized that it placed a load on working memory that interfered with prespecified search guidance. However, Kerzel and Grubert (2022) have recently provided evidence that two attentional templates (e.g., two colors) can be active simultaneously, though search performance decreases were unclear. Similarly, Liu and Jigo (2017) found that two colors could be attended to and improve performance in comparison to no color guidance, but single-color guidance performed best. Stroud et al. (2012) observed that two search targets, close in color (e.g., orange and red), had faster response times than two distinctly different-colored targets (e.g., orange and green). Importantly, Stroud et al. (2012) also found single-color search had significantly faster response times and lower error rates than any dual-color target search. Thus, while multiple-color attentional guidance is possible, it appears to come at a search performance cost, compared to single-color or similar color attentional guidance.

Prior research has shown that humans can miss highly visible objects in their visual scene when their attention is directed elsewhere; this phenomenon is called inattentional blindness (Mack & Rock, 1998; Simons & Chabris, 1999). Inattentional blindness is a consequence of tuning selective attention, which may result in ignoring more than the intended irrelevant information. Simons and Chabris (1999) demonstrated inattentional blindness by having participants count the number of basketball passes made by players wearing either white or black team clothing. In the dynamic scene, where players on both teams moved around, intermixing, and two basketballs passed back and forth, a person dressed in a black gorilla suit walked into the center of the scene, thumped their chest, then walked out of the scene. Shockingly, half of the participants attending to the white team failed to notice the gorilla, which was on screen for 9 seconds. Simons and Jensen (2009) observed that inattentional blindness rates increased when the primary task difficulty increased.

Multiple-color visual search may result in inattentional blindness when observers are engaged with a demanding search task and the number of potential target colors exceeds the capacity of the number of colors that can guide attention. Only one or two discrete colors at any given time appear to be able to guide search, and this additional guidance may increase the likelihood of missing unattended or unexpected alternate target colors (e.g., searching for green and orange while missing pink). Wood and Simons (2017) have previously shown inattentional blindness with participants performing a multiple object tracking task. They found that participants noticed unexpected objects when they aligned with their attentional set more often than novel, unexpected objects that did not align with their current attentional set and were effectively suppressed with “everything else”. Interestingly, Wood and Simons did observe an increase in noticing a novel, unexpected “green” object when participants were tracking objects of various colors (i.e., yellow, red, black, and purple) and ignoring “white” objects compared to vice versa. Wood and Simons explained that the increased noticing rate for the unexpected “green” object may be because “green” fits within an attentional set for “colored” or “non-white” versus “white.” However, when the tracked object did not vary by color within a specific trial (e.g., white versus purple rather than white versus yellow, red, black, and purple), then the unexpected, novel “green” object was noticed less often. Overall, their evidence suggests participants guided their attention using a category-level (i.e., “white” versus “non-white”) rather than a feature-level (i.e., enhance white while suppressing yellow, red, black, and purple) attentional set.

However, the effectiveness of guidance based on an attentional set may be influenced by the similarity of an unexpected object to the target and other distractors. Drew and Stothart (2016) found that unexpected objects with greater target color similarity had higher noticing rates, specifically when the unexpected object was similar in color to the target while not sharing close color space with distractor colors. For example, if the target is blue and the distractors are green, then an unexpected object is more likely to be noticed if its color is magenta rather than cyan. This is similar to Stroud et al.'s (2012) finding of improved search performance for targets with more similar colors. Together, these studies support a recommendation to have lifesaving equipment more similar in hue as well as a caution that multiple-color search may reduce search performance.

5.2.3 History, Value, and Scene Guidance

Wolfe's (2021) Guided Search 6.0 has added three other types of guidance: history, value, and scene. Awh et al. (2012) observed that the history effect emerged when an observer had previously searched for an object. For example, a SAR responder finding a first PIW wearing a green life jacket is passively primed to find a second PIW also wearing a green life jacket. Anderson et al. (2011) found that value-driven guidance influences an observer's subsequent search behavior based on their prior positive or negative values associated with specific features. This results in a reward effect (either physical or psychological) for detecting an object. Scene guidance relies on an observer's knowledge of the scene syntax (i.e., constraints of the scene) and semantics (i.e., meaning of the scene) that influence where an observer expects to find an object (Wolfe, 2021).

6 DISCUSSION & CONCLUSIONS

6.1 Colors

Many high conspicuity colors were identified during the regulatory, industry standard, and literature review. A consolidated list is contained in Table 5.

Table 5. Summary of high conspicuity colors from regulatory, standards, and literature review.

Regulatory Review	Standards Review	Literature Review
Indian Orange [a]	Florescent Yellow-Green [h, i, j]	Fluorescent Green [l]
International Orange [a, b, c]	Fluorescent Yellow [d, f, g, j, p]	Fluorescent Green-Yellow [i]
Orange [a]	Fluorescent Yellow-Orange [d, f, g]	Fluorescent Lime-Yellow [s]
Scarlet Munsell 7.5 Red 6/10 [a]	Fluorescent Orange [d, f, g, p]	Fluorescent Orange [q, s, t, u, w]
Vivid Reddish Orange [a, b, c]	Fluorescent Orange-Red [d, f, g, h, i]	Fluorescent Red [r]
White [a]	Fluorescent Red [d, f, g, h, p]	Fluorescent Red-Orange [k, m, n, o, r]
	Fluorescent Red-Orange [g, p]	Fluorescent Yellow [q, k, v]
	Fluorescent Green [p]	Fluorescent Yellow-Green [m, n, o, r, u]
	Indian Orange [f]	Fluorescent Yellow-Orange [k]
	International Orange [f]	White [s]
	International Orange-Yellow [e]	
	Orange [d, f, g]	
	Red [d, f, g, j]	
	Scarlet Munsell 7.5 Red 6/10 [f]	
	Vivid Reddish Orange [f]	
[a] 46 CFR §160	[i] U.S. Department of Transportation	[q] Zwahlen & Vel (1994)
[b] SOLAS Convention/LSA Code	[j] NFPA	[r] Turner et al. (1997)
[c] IACS	[k] Halsey et al. (1955)	[s] Isler et al. (1997)
[d] ISO	[l] Uglene & Tahermaram (2011)	[t] Killeen (2005)
[e] SAE International	[m] Sayer & Mefford (2005)	[u] U.S. Fire Administration (2009)
[f] UL Solutions	[n] Sayer & Mefford (2006)	[v] Krull (2000)
[g] ANSI/CAN/UL	[o] Buonarosa & Sayer (2007)	[w] Hawkins et al. (1998)
[h] ANSI/ISEA	[p] ANSI	

Generally, colors adopted by regulation or standard, or further investigated through various high visibility studies included hues of green, yellow, orange, and red. The exception is White, which was observed to be highly visible in specific conditions but ineffective across a variety of scenarios. In typical maritime SAR conditions, both Creedon (1948) and Halsey et al. (1955) recognized White would easily be overlooked or mistaken for white-caps, flotsam, or possibly sea birds.

Halsey et al. (1955) also found high saturation and/or high brightness colors performed best among standard colors, with the exception of hues of yellow and white, which were often misidentified at distance or not detected at all. Since SAR operations often occur in advanced sea states with abundent white-caps, yellows and whites were omitted. Hues of orange and red, while not the most detectable in all conditions, performed best across the broadest range of scenarios.

6.1.1 Conspicuity of Yellow at a Distance

Hues of yellow appear frequently in the literature, commonly for highway safety applications. Early maritime studies by Malone et al. (1951) found Yellow to be least detectable at sea when compared to yellow blends (e.g., Yellow-Red) and red hues. While Yellow has high conspicuity at close range, observers often misidentified it as White at further distances (Halsey et al., 1955). Given the discussion on white hues in Section 6.1 and the distance from which SAR assets may conduct searches, it is likely yellow targets would be overlooked or mistaken for irrelevent objects as well.

6.1.2 Fluorescent Colors

Fluorescent colors have been shown to involuntarily attract the attention of observers, both in direct and peripheral vision (Schieber et al., 2006). They are more conspicuous during daylight hours, including the low-light times of dusk and dawn, than their standard color counterparts (Hawkins et al., 1998; Krull, 2000; U.S. Fire Administration, 2009). Halsey et al.'s 1955 report concluded the detectibility of Fluorescent Yellow-Orange and Fluorescent Red-Orange far exceeded all standard (i.e., non-fluorescent) colors. Importantly, Halsey et al. did not include Fluorescent Green in their tests.

Due to concerns (in the mid-1950s) with the color fastness (hereon used interchangeably with *color permanence*) of fluorescent dyes and paints, fluorescent colors were not further considered for lifesaving equipment. Fluorescent color permanence concerns continue to appear in literature, though the degree of color fastness varies greatly among fabrics, dye processes, coatings, and base materials. High visibility safety apparel subjected to repeated washing and ultraviolet (UV) light exposure in accordance with ISO 105-B02 – *Textiles – Tests for colour fastness – Part B02: Colour fastness to artificial light: Xenon arc fading lamp test* yielded mixed results; Vijayan et al. (2015) observed reactive fluorescent dyes used for cotton demonstrated significant resistance to color fade compared to the disperse dyes used for polyester. However, Park (2019) tested high visibility garments to ISO 20471 – *High visibility clothing* – Test methods and requirements, which also contains Xenon arc UV exposure criteria, and observed only minor changes in color fastness. Lifesaving equipment not constantly exposed to UV light (e.g., life jackets stowed within a ship) may benefit from fluorescent color use.

6.1.3 Color Patterns

Color patterns are another means of increasing conspicuity by drawing the attention of observers. Multiple patterns are currently used in highway safety and emergency response. While there has been work on identifying a single-most effective pattern, an overarching theme is placing highly contrasting colors in an unnaturally occurring pattern (i.e., one not typically seen in the natural environment). The colors used in these patterns tend to be high chromaticity colors adjacent to high luminance colors, such as the Red and Yellow chevron recommended for fire apparatus by NFPA 1901. Importantly, visual search in a maritime domain can be over several nautical miles such that distance may affect color pattern conspicuity.

7 RECOMMENDATIONS

7.1 Color Recommendations

From the review of domestic and international regulations, industry standards, and research literature, the following colors are recommended for future testing:

- International Orange or U.S. regulatory equivalent (control).
- Fluorescent Green.
- Fluorescent Orange.
- Fluorescent Pink.[4]
- Fluorescent Red.

The colors White and Yellow are not recommended other than for comparison purposes. The project sponsor may desire alternate and/or non-fluorescent colors be tested in addition to those listed above. The RDC will garner consensus from the sponsor when identifying the final colors testing palette for field trials.

7.2 Field Tests Experimental Plan

Using the colors identified in Section 7.1, an experimental plan for upcoming field tests will be developed by the RDC with input and concurrence from the Project Sponsor. In the marine environment, the background color can change based a SAR responder's point of view (e.g., aircraft or surface asset), water body, water depth, proximity to land, ambient lighting, weather, sea state, etc. The sheer number of variables indicates that no single color is the most detectable in every scenario; however, colors can be evaluated for optimum detectability in specific situations as well as over the broadest range of conditions.

The primary aim of future testing is to determine and validate optimally visible color(s) aiding in the detection of search objects across various marine environment conditions. A secondary aim is recommended to investigate the impact that single- versus multiple-color visual search has on object detection in the marine environment. The proposed locations of initial field tests are Long Island Sound between the Connecticut and Long Island, New York coastlines, Block Island Sound, and Cape Cod Bay. Conducting field tests in additional project-relevant geographic locations will be explored as opportunities arise. Examples of relevant locations include the Arctic, Gulf of Mexico, and the Great Lakes.

7.3 Policy and Regulatory Considerations

If a change in approved lifesaving equipment color occured, selecting a hue close to existing USCG-approved colors may limit search performance costs.

[4] Sponsor recommendation based on current use of fluorescent pink in marine environment.

7.4 Future Research

7.4.1 Color Patterns and Maritime Conspicuity

The effectiveness of color patterns to increase detectability in the maritime environment has received little if any attention. Due to the distance at which SAR responders may conduct a search, patterns would likely be most effective on large surfaces such as liferaft and lifeboat canopies. While the scope is broad enough for a dedicated research project, a patterned target could be included in this project as an additional data point.

7.4.2 Color Fastness

Color permanence studies on USCG-approved lifesaving equipment would help determine the duration that lifesaving appliances continuously exposed to UV light remain within specified color standards. Currently, lifesaving equipment is visually examined by USCG marine inspectors or classification society surveyors, typically with an emphasis on physical degradation that would affect functional performance. The degree of color fastness is difficult to determine by the naked eye, and the potential exists for lifesaving equipment to remain onboard vessels well after fading beyond approved color thresholds.

7.4.3 Materials, Coatings, and Finishes

As noted by UL Solutions (2019), additional information on lifesaving equipment materials, and in particular base materials, coatings and finishes, would be helpful in understanding their impacts on actual versus theoretical color presentation. Dye processes for woven, natural fabrics may display differently than those for synthetic fabrics. The same can be said for pigments used in paint and rubberized coatings, particularly when applied on a variety of base materials. These variables may also affect color fastness, discussed in Sections 6.1.2 and 7.4.2, and could be combined with a study of materials, coatings, and finishes to comprise a single research project.

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APPENDIX A. DEFINITIONS

Achromaticity	In relation to color vision, the failure to distinguish colors with low luminance due to insufficient energy to stimulate the eye's color receptor cones (Davson, 1980).
Chromaticity	The color quality of color stimulus definable by its chromaticity coordinates, or by its dominant (or complementary) wavelength and its purity taken together (International Association of Marine Aids to Navigation and Lighthouse Authorities [IALA]. [n.d.], 2023).
Coast Guard Approved	Lifesaving equipment certified to meet U.S. Coast Guard specifications, standards, and regulations for performance, construction, and materials (U.S. Coast Guard Boating Safety Division, 2012)
Color Space	A completely specified scheme for describing the color of light, ordinarily using three numerical values called coordinates (Kerr, 2010).
Conspicuity	The ability of an object to stand out from its surroundings (IALA. [n.d.], 2023).
Detectability	The ability of an object to be discovered, or presence determined (Merriam-Webster. [n.d.], 2023).
Flag State	The country or nation (also referred to as *state* internationally) in which a vessel is registered. The term *flag state* comes from ships registering with a country, then flying that flag to denote registration with that country (Maritime Institute of Technology and Graduate Studies [MITAGS], 2023).
Fluorescence	Fluorescence is the process by which electromagnetic radiation of one wavelength is absorbed and re-radiated at another wavelength. Fluorescence and ordinary reflectance take place simultaneously and at the same wavelengths (IALA. [n.d.], 2023).
Foreign Vessel	A vessel of foreign registry or a vessel operated under the authority of a country except the United States (Foreign Vessel, 2021).
Intervention	A control action taken by a port state to bring a foreign flag vessel into compliance with applicable international convention standards (Intervention, 2016).
Luminance	Light emitted by a surface; for non-light generating objects, luminance relies on the light incident on that object, the light intensity, and angle(s) of diffusion from that object. From a psychophysical perspective, luminance is perceived by the human eye as brightness (Davson, 1980). Luminance is measured as light energy per unit area.

Luminosity	The attribute of visual sensation according to which an area appears to emit more or less light (IALA. [n.d.], 2023), measured as light energy emitted per unit time.
Passenger Vessel	On an international voyage, a vessel carrying more than 12 passengers, including at least one passenger for hire (Passenger vessel, 2021).
Port State	A country or nation (also referred to as *state* internationally) that allows or exercises Port State Control (see definition, below) at its ports (Maritime Institute of Technology and Graduate Studies [MITAGS], 2023).
Port State Control	The process by which a nation exercises its authority over foreign vessels in waters subject to its jurisdiction (Port State Control, 2016).
Psychophysical	The effect of physical processes (such as intensity of stimulation) on the mental processes of an organism (Merriam-Webster. [n.d], 2023).
Response Time	The time from when an object or stimulus is presented until its detection or identification (Wolfe, Guided search 6.0: An updated model of visual search, 2021).
Visual Search	The process of scanning the surrounding environment with the intent of detecting a specific object or visual stimulus (Wolfe, Guided search 6.0: An updated model of visual search, 2021).