Re-evaluating High Visibility Colors of Lifesaving Equipment Used by the Coast Guard

Abstract

A major role of the U.S. Coast Guard involves conducting search and rescues for boating accidents. Our project aimed to design an experiment to reevaluate high visibility colors of marine lifesaving equipment. To accomplish our goal, we researched past experiments to investigate the procedures and variables used to test the visibility of various colored objects. We interviewed USCG personnel regarding search and rescue procedures as well as the technology used to aid search and rescue. Interviews with other mariners identified how human perception is used when searching for objects in the water. We then developed an experimental protocol that will enable the Coast Guard to test a chosen color palette to determine if the current Indian-Orange color is more visible than other colors in the marine environment.

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Reevaluating Lifesaving Equipment Colors to Increase Visibility of Stranded Victims

The Coast Guard is a unique branch of the military responsible for protecting and defending America's coastlines and waterways. They achieve this goal through multiple missions, including environmental protection, customs enforcement, and defense operations. While protecting the waterways, they also serve a critical role in search and rescue missions due to boating accidents. The Coast Guard must rely on the high visibility colors of life saving equipment to locate survivors in adverse marine conditions[1].

For almost 65 years, the color specifications for the equipment have been constant. The United States Coast Guard (USCG) last thoroughly tested color visibility in 1955. The testing of visibility took place only in clear conditions and did not consider adverse weather. This 1955 study concluded that yellow and red-oranges were the most visible colors during clear weather conditions[2]. Thus, Indian Orange became the regulated color for Coast Guard lifesaving equipment. Although the technology used in search and rescue has evolved and improved over the years, the color of lifesaving equipment has not been reexamined.

The hardest part of search and rescue missions is finding the stranded victims. Different weather conditions on the water can lower clarity of vision and completely obscure survivors. Some examples of these adverse conditions are fog, heavy rain, snow, and glare from the sun on the water. Even with the current technology available for search and rescue, the weather still plays a huge role in inhibiting visibility out on the water. This project's goal was to investigate the factors that affect the visibility of colors and design an experiment to test colors that might provide better visibility when searching for a victim in adverse weather conditions. An experimental design was presented to the Coast Guard, who will be able to conduct the tests specified in the design to determine whether the current Indian Orange is still the most visible color in adverse marine conditions. To achieve this goal, the research team outlined three main objectives:

1. Investigate the procedures and variables used in past experiments;
2. Understand how human perception is used when searching waters for objects by utilizing insight on Coast Guard search and rescue procedures and technologies;
3. Prepare a final design of an experiment to reevaluate the high visibility color of lifesaving equipment.

To address these objectives, the team researched past experiments to identify variables that were considered the most important to the visibility of colors in various environments. Interviews with USCG personnel led the team to understand the procedures used for search and rescues, as well as the technologies used. Additionally other mariners were interviewed to learn more about the role of human perception in finding objects in the water. This led to the development of an experiment assessing a chosen color palette and determining the most visible color for use in lifesaving equipment. Various factors are known to affect the visibility of objects to a human observer. These factors include human perception, color contrast, conspicuity, reflection, and weather conditions.

Visibility is Influenced by the Physical Limits of the Human Eye

Visibility refers to "the quality or state of being visible"[3] with visible meaning "capable of being seen" or "exposed to view"[4]. To detect means "to discover or determine the existence, presence, or fact of", therefore detectability refers to the state of being discovered[5].

The visibility of an object is influenced by "the constraints on the side of the observer, the effects of environmental conditions… and the properties of the object itself" and the surroundings[6]. "Normal" vision is defined as having 20/20 eyesight. Having 20/20 vision means being able to see what a person can see on a standard medically approved eye chart standing 20 feet away. Thirty-five percent of adults have 20/20 vision without any correction; with correction, 75% of adults have 20/20 vision[7].

Visual acuity plays an important role when measuring the ability of one's vision. There are three types of visual acuity: detection, resolution, and recognition. Detection acuity is defined as the ability to detect a target such as a small target against a dark background[6]. Resolution acuity is defined as the ability to detect a separation between discrete elements making up a pattern[6]. Recognition acuity is the most widely-known measure. This is gauged using the Snellen eye chart commonly seen in an eye doctor's office[6].

Vision is made up of light sense, color sense, and form sense[8]. Light sense is the awareness of light and of modification in its intensity. Color sense allows humans to distinguish between the qualities of two or more lights in terms of their wavelengths. Form sense permits the discrimination of the different parts of a visual image. The rods in the retina are responsible for night vision. The fovea, which is made up of only cones, is blind at low intensities of illumination. This means that, in low light, human vision is reduced greatly. At low luminance, the eye fails to distinguish colors as well as it does in daylight[8].

The Luminance and Contrast of Color Help Objects Stand Out More

Luminance is defined as “the amount of light that reaches the eye from a given direction of space and roughly correlates with the experience of brightness”[9]. Luminance is one of the primary variables measured in visibility tests. The higher the percentage of light that reflects off a surface, the higher the luminance[9]. The luminance of colors directly relates to the wavelength spectrum.

Although luminance is one of the main factors, visibility also depends on physical contrast, or “the difference in light intensity between the image and the adjacent background relative to the overall background intensity”[10]. For example, if a sheet of white paper is held next to snow in bright conditions, the visibility of the sheet of paper would be low due to the lack of contrast, even though its luminance is high. This principle relates to the lifesaving equipment for marine conditions. If the color of a life jacket is too dull, it will not contrast well in dark rainy conditions, so the visibility will be low. That is why both luminance and color contrast must be measured when testing for visibility of different colors. They are the two main factors tested when checking a color’s visibility.

The Sensitivity of the Human Eye to Light Affects Perception

Human perception only allows an eye the ability to see light wavelengths from 390nm (nanometers) to 700nm as shown in Figure 1. A light-adapted eye generally has its maximum sensitivity at around 555nm, in the green-yellow region of the optical spectrum[11]. In other terms, in day-light conditions, the human eye detects the green-yellow region to be the “brightest” color compared to others. In low light conditions, the maximum sensitivity drops to 507nm. The green region becomes the “brightest” color during the night.

Conspicuity is defined as the process of an object being detected by an observer. The color and brightness of an object affect whether or not it is seen. In addition to this, brightness has more of an impact affecting visibility than the color of an object does. The brightness of an object refers to the “intensity of the visible spectrum that is reflected back to the viewer”[12]. Brightness and luminance both have an intensity scale based upon the percentage of light or visible spectrum being reflected off a surface into an observer’s eye. Color is defined by which wavelengths of light are reflected back to an observer’s eye. Fluorescent colors appear unnatural which causes them to be highly conspicuous to the eye[13].

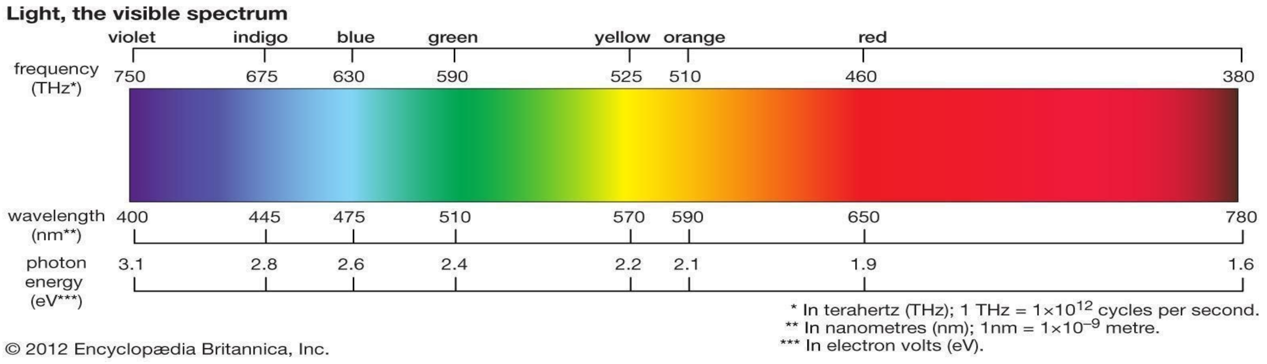


Figure 1: Light, the visibility spectrum[6]

Light Interacts Differently Depending on the Surface

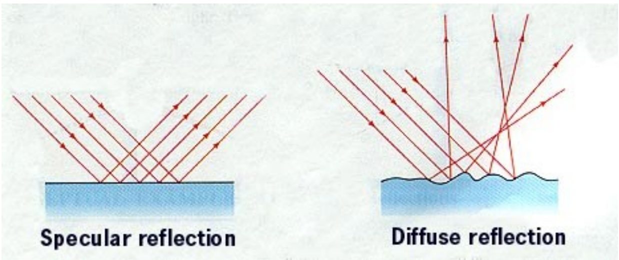


Figure 2: Visual Diagram of Specular and Diffuse Reflection[16]

In order to properly measure visibility and understand the ways light interacts with different surfaces, understanding transmission of light is imperative. Two relevant interactions between light and objects are reflection and refraction, the more important being reflection.

Reflection occurs when light bounces off an object[14]. There are two types of reflection, specular and diffuse reflection, as depicted in Figure 2. Specular reflection exists when light reflects off a smooth surface at the same angle as it hits the surface. With diffuse reflection, light hits an object with a rough surface and reflects in different directions.

The light coming in at the object is called an incident wave whereas the light bounced off is called the reflected wave. The Law of Reflection states that the angle of incidence is equal to the angle of reflection for visible light. The amount of light reflected by an object and the way in which it is reflected depends on the texture of the surface[14].

Refraction is the bending of a wave when it enters a denser medium which causes it to reduce in speed. This generally occurs when light goes through clear or opaque objects, such as glass, water, and plastic. The angle of refraction, or the measure of the change in angle due to the bending of the light as a result of passing through a medium, is dependent on the value of the index of refraction. The index of refraction is defined as the speed of light in vacuum divided by the speed of light in the medium. The density of the material directly relates to the speed of light in the material. The higher the density of the material, the more the light bends upon entry. For water, the index of refraction is 4/3, which means that light in water travels at 3/4 the speed of light in a vacuum. This results in visual bending to light when it is in water[15].

The Effects of Light Scattering are Dependent on Environmental Conditions and Wavelengths

Particles in the air affect visibility by scattering, and absorbing light. Scattering is a phenomenon which consists in the re-emission in many directions of a beam of light, this occurs when a beam of light strikes particles of variable size present in a solid, liquid, or gaseous system[17]. Rayleigh Scattering, as exhibited in Figure 3, is a type of light scattering caused by smaller particles, such as nitrogen, oxygen, and carbon dioxide. These commonly occur as gasses in the air and are present regardless of the weather condition in the troposphere. Not all wavelengths of light are affected the same with Rayleigh Scattering. Shorter wavelengths on the blue end of the spectrum tend to be scattered more than longer wavelengths. This means that red wavelengths are more likely to travel the farthest along a straight path, thereby being more visible over long distances. This can be seen at sunrise or sunset, as the light appears more red because it has to travel a longer distance and more blue light is filtered out due to Rayleigh Scattering.

The other type of light scattering, Mie Scattering occurs with larger scattering centers than Rayleigh Scattering. For this reason, Mie scattering occurs when light is scattered by larger particles such as water vapor and reduces overall visibility in all visible wavelengths. An example of Mie Scattering is fog[17].

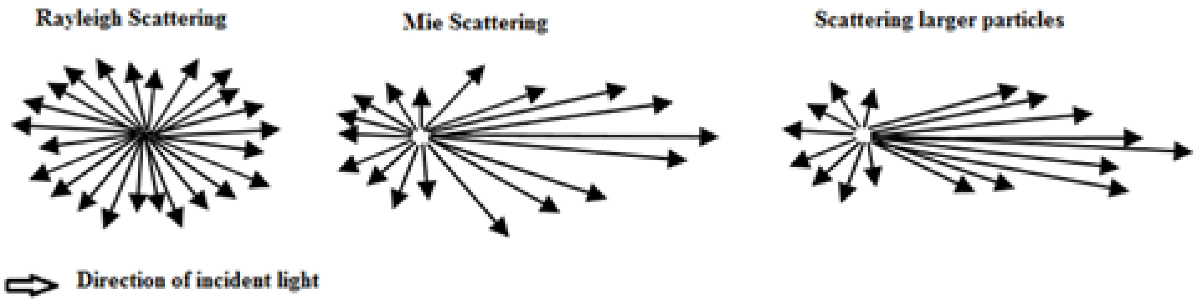


Figure 3: Rayleigh and Mie scattering[17]

Night Vision Goggles Enhance Visibility at Night

While conducting search and rescue missions at night, the Coast Guard must rely on technology and retroreflective material. During the night, the amount of ambient light significantly lowers compared to the daytime, causing objects and people in the water to become harder to locate. Night vision goggles (NVGs) are used by the USCG when conducting search and rescue at night. Night vision goggles do not provide perfect night vision, but they do enhance visibility at night significantly.

NVGs allow an observer to create artificial ambient light to see at night. There are two types of goggles the Coast Guard uses at night, image enhancement and thermal imaging. Image enhancement, the most widely known type of night vision, collects ambient light, then transfers all light to a green phosphor image. The camera captures the ambient light, and sends it to an image-intensifier tube. The image-intensifier tube has a photocathode, which converts photons of light energy into electrons. At the end of the image-intensifier tube, the electrons hit a screen coated with phosphors. The electrons maintain their position in relation to the channel[18]. The observer then sees a perfectly clear green phosphor image through an ocular lens.

Night vision goggles are effective for amplifying light in low visibility conditions, however, they do not work in all conditions. In low visibility conditions such as fog and smoke for example, light cannot be seen through the NVGs. In these conditions, thermal imaging is used instead. The main difference between image enhancement and thermal imaging is that night-vision looks at the reflected light from different objects, while thermal imaging looks at the infrared radiation different objects give off. Wavelengths in the infrared spectrum are slightly longer than the wavelengths of light in the visible spectrum, making it only visible through thermal imaging[18].

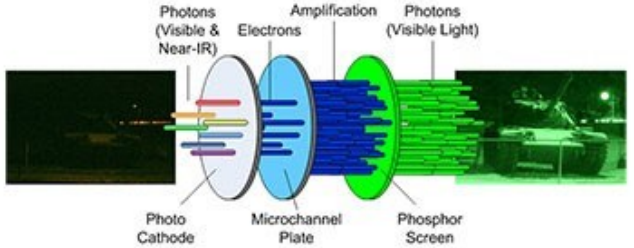


Figure 4: How Night Vision Goggles Process Light[19]

Fluorescent Colors Stand Out More to the Eyes

The colors of objects are dictated by the wavelengths of light that they reflect. When an object appears a certain color while illuminated by white light, the object reflects light of that color and absorbs all other colors[20]. For example, a red apple reflects red light and absorbs all other colors. A black object absorbs all colors and reflects no light, making it the darkest color. White objects reflect all wavelengths of light, absorbing no light. The more light an object absorbs, the more heat it radiates. Darker colors absorb the most heat[20].

When trying to identify the most visible colors, it is important to consider what colors reflect the most light. The more light an object reflects, the brighter it appears, thus making it easier to see. Fluorescent colors are brighter versions of the colors on the visual spectrum. This is because the electrons in fluorescent pigments absorb light energy and are temporarily promoted into high-energy orbitals. Then, when the electrons settle back down into their regular position they emit light in a fluorescent shade[20]. The fluorescent shade is what makes fluorescent colors appear significantly brighter than non-fluorescent colors. In the marine environment in adverse conditions, colors that pop out compared to the dark sea or white cap environment are what will be seen the easiest.

The Beaufort Scale Categorizes Sea State From Calm to Hurricane Conditions

The Beaufort wind force scale measures the force of wind, which is ranked from 0-12[21]. The Beaufort scale gives estimates for wind speed and sea state[22]. Sea state is characterized by the condition of the waves at sea which includes wind speed, wave height, and visual characteristics of the sea as observed from land and water[23]. Wind speed is the main cause for waves. The Beaufort scale categorizes wind conditions starting with calm wind depicted as Beaufort number 0 with 0 knots of wind and no waves[22]. Wind and wave conditions gradually increase moving up the scale ending with Beaufort number 12, described as a hurricane. The sea state for the Beaufort scale of 12 includes over 64 knots of wind, over 45 foot waves, and from a visual standpoint, the sea is filled with whitecaps and visibility is very limited.

Weather Conditions Obscure Visibility of an Object

Coast Guard search and rescue teams conduct missions in a variety of adverse weather conditions. These weather conditions can vary among: fog, rain, snow, sun glare, etc. These conditions usually do not prevent the Coast Guard from launching their boats or lifting their aircraft. However, some conditions make search and rescues harder to perform, such as dusk and snow.

When searching at dusk, the glare from the sun is blinding. As the sun is almost at eye level with the water, this causes any object in the water to become nearly invisible[24]. Sun glare can be so blinding at times that it can restrict the ability to perceive objects located ahead. It reduces the “sensation of contrasts [and] sharpness”[25]. Sun glare primarily affects visual perception, impairing visibility distance and sight where temporary blindness occurs. There are two kinds of impacts from the effects of sun glare, direct and indirect. Direct impact is when the sun shines directly into one’s face. Indirect impact is when the light from the sun is reflected off another surface and then into the eyes. Indirect impact could be reflection off any lifejacket, boat, water, or even snow[25].

Fog is a weather condition whereby small droplets of water are lofted into the air and form a low hanging cloud that can obscure visibility. There are several situations that can cause this to occur, however on the ocean the type that generally occurs is steam fog. It is formed when cold, stable air moves over a much warmer body of water. Evaporation from the warm body of water saturates the cold air above; water vapor condenses in the cold air, producing fog. This type of fog is generally dense and can greatly reduce visibility. The term “fog” is used when microscopic droplets reduce horizontal visibility at the Earth’s surface to less than 1 km[26].

Developing an Experimental Design Theory

The experimental design theory must begin by defining the problem statement or objective. The experiment must first define what the key objectives are. In other words, what is the goal the experiment is attempting to accomplish. Once the objective is defined, a list of all process variables must be determined. Process variables include the: inputs, levels, and outputs. The input variables are also known as factors, the levels are also known as controls, and the output variables are known as responses. After the objective and process variables have been determined, the experimental design must be defined. The experimental design is dependent on the objective and number of factors being investigated[27].

Analyzing a Full Factorial Experiment

Multi-factor experiments are designed to evaluate multiple factor sets at multiple levels. One example of a multi-factor experiment is a “full factorial experiment.” A full factorial experiment is when each factor is tested at each level in every possible combination with the other factors and their levels[28]. In other words, a full factorial experiment is when each variable is tested in combination with each control. For example, a full factorial experiment would be testing a red buoy and an orange buoy in both rainy and foggy weather conditions, if red, orange, rain, and fog were the only variables defined in the experiment. The number of trial runs in a full factorial experiment is determined by the number of factors and controls. The equation of **# of factors**$^{\#\text{ of controls}}$**= number of runs full factorial**[28]. In some experiments where the number of combinations of factors and levels is unachievable, the experiment can be split into a fractional experimental design[29]. However, a fractional experimental design would result in a smaller confidence interval as not all factors and levels are tested in combination. To achieve the greatest confidence interval, a full factorial experiment must be conducted.

Developing an Experiment to Reevaluate Lifesaving Colors

To achieve our goal as visualized in Figure 5, the team had to develop background knowledge on search and rescues. Literature reviews and interviews led to an understanding of key components that helped develop the experimental design.

Literature reviews allowed the group to understand the experiments that have been performed in the past and the methods that were

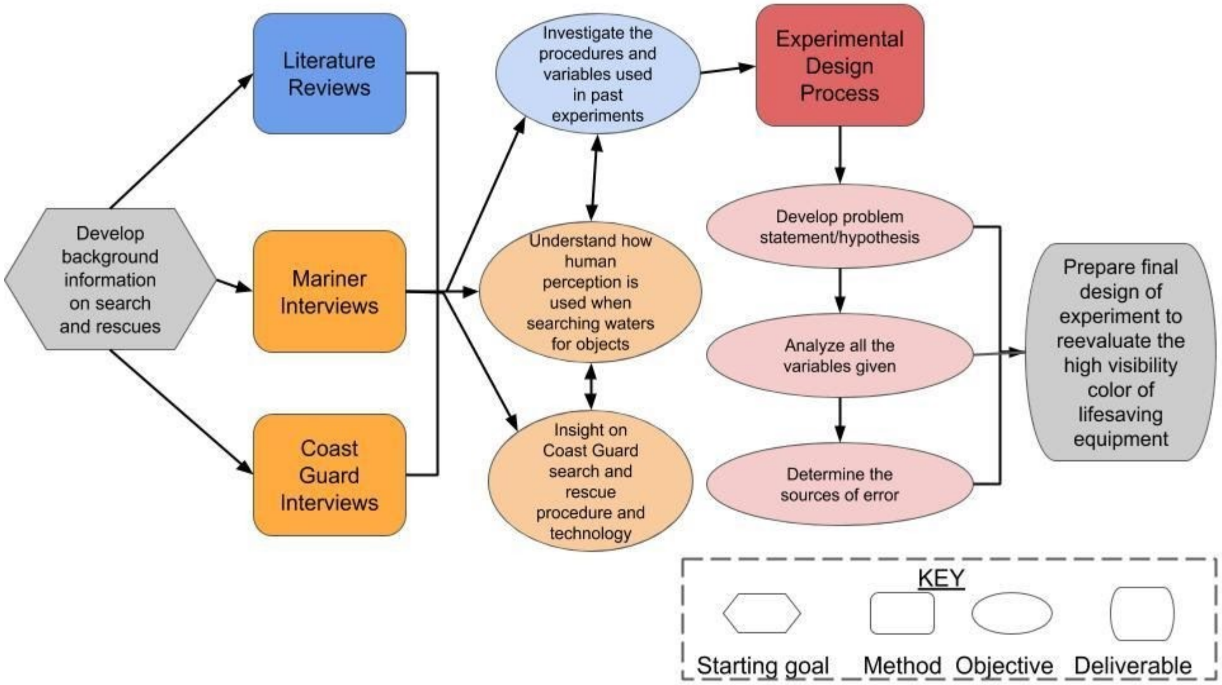


Figure 5: IQP Project Goal Flowchart

previously employed to evaluate color perception. By analyzing the variables in other experiments, the team could determine the impact of each variable, identifying which variables should be incorporated into the experimental design.

Interviews led to gathering information from current participants in the fishing and marine industries. The team learned about each fishermen's personal experience working in adverse marine conditions and what equipment is used to assist them searching for objects in the water. The information gained from these interviews helped the team in three ways. First, interviews alerted any major factors that were not obtained from the literature reviews. Second, information generated from ongoing interactions with Coast Guard personnel was used to refine the experimental design. Third, members of the Coast Guard with experience in adverse conditions have valuable insight on the most visible colors in these conditions.

Once the team obtained the preliminary information from literature reviews and interviews, the process of developing the experimental design began. The background research gathered guided the team in developing the problem statement, analyzing the most important variables that affect the visibility of color, and determining possible sources of error that occurred in past experiments. After analyzing the background information gained from research, the team fully designed the procedure to reevaluate high visibility colors of lifesaving equipment in adverse marine conditions.

Figure 6: Colors used in the Mustang Survival Experiment. From top to bottom: fluorescent green, fluorescent orange, non-fluorescent red, and non-fluorescent yellow[30]

Procedures and Variables Used in Past Experiments

In order to develop a solid experiment to test whether the current red-orange color used in lifesaving equipment is the most visible color, we first sought to understand how that color was originally chosen, based on the 1955 Coast Guard field study[2]. In addition to the 1955 study, the team also reviewed nine past experiments, on the visibility of color to identify and evaluate the variables that were chosen by researchers to conduct experiments on color and visibility. Three of these studies provided the most significant factors for our investigation and are discussed here.

Fluorescent Green Tops in Mustang Study

The Mustang Survival experiment, completed in 2011, tested four different colors for their visibility in a simulated environment and physically on the water. The experiment was conducted with 14 viewers, all adults, half male and half female. The viewers were the subjects on whose reaction the Mustang Survival team based the results of visibility of the four different colors that were being tested. These viewers consisted of non-boaters, recreational boaters, coast guard auxiliary, private pilots, and commercial fishermen. The experimental observers were one of Mustang's control variables for their experiment.

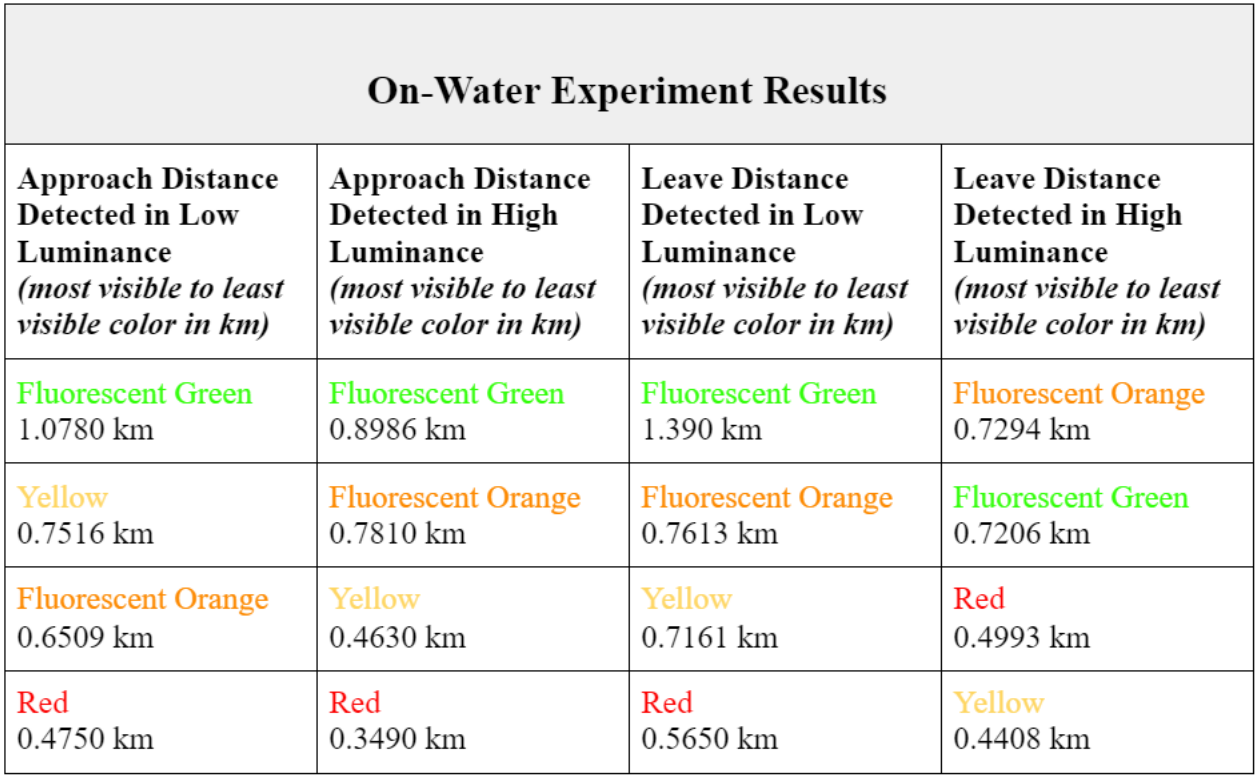
The colors the viewers were observing were: fluorescent green, fluorescent orange, non-fluorescent red, and non-fluorescent yellow, as seen in Figure 6. The color, fluorescent green, was chosen to test because of how vibrant it is although it is not considered as an acceptable color for use in North American lifesaving equipment. Fluorescent orange was chosen for testing due to it being used on US immersion suits for nearly two decades. Non-fluorescent red was chosen because it is used on many anti-exposure coats and work suits. Non-fluorescent yellow is used extensively on immersion suits and inflatable personal flotation devices (PFDs) [30]. Two fluorescent colors were chosen to be tested for the Mustang experiment because a study by the Illinois Transportation Research Center concluded that fluorescent colors were most visible under low light conditions present at dusk and dawn. Two non-fluorescent colors were chosen to compare the visibility of commonly used colors on safety equipment to new colors. The color of the target buoy was one of two independent or input variables for the experiment.

The most valuable information from Mustang Survival's experiment came from the "On-Water Environment" test. This information is valuable because the on-water factor involved directly relates to potential Coast Guard needs. For the "On-Water Environment" test, Mustang anchored colored target buoys directly in front of the test boat. The test boat was then driven towards and away from the target buoys until the viewers could physically see them (or no longer see them) in both high luminance and low luminance conditions. The way the boat would travel, towards or away from the object, was the second independent variable for Mustang's experiment.

Figure 7 shows what the on-water conditions were for the testing experiment. The distance between the buoys and point where the viewers were able to recognize them was calculated using the great circle distance formula[30]. Their data was portrayed in tables that showed the mean furthest distance of detection for each color. The detection distance was the only dependent variable that can be identified in the Mustang Study. Detection distances were measured based on how far the object was detected by the observers and not based on correct color being detected. Correct color detection was noted in the report; however, it was not included in the data analysis.

The results of the "On-Water Environment" experiment, as seen in Table 1, concluded that people should, "WEAR FLUORESCENT GREEN TO BE SEEN." Table 1 shows the furthest distance, in km, at which the buoys with

Table 1: Results from the Mustang Survival On-Water Environment Test[30]



On-Water Experiment Results

Approach Distance Detected in Low Luminance *(most visible to least visible color in km)*	**Approach Distance Detected in High Luminance** *(most visible to least visible color in km)*	**Leave Distance Detected in Low Luminance** *(most visible to least visible color in km)*	**Leave Distance Detected in High Luminance** *(most visible to least visible color in km)*
Fluorescent Green 1.0780 km	Fluorescent Green 0.8986 km	Fluorescent Green 1.390 km	Fluorescent Orange 0.7294 km
Yellow 0.7516 km	Fluorescent Orange 0.7810 km	Fluorescent Orange 0.7613 km	Fluorescent Green 0.7206 km
Fluorescent Orange 0.6509 km	Yellow 0.4630 km	Yellow 0.7161 km	Red 0.4993 km
Red 0.4750 km	Red 0.3490 km	Red 0.5650 km	Yellow 0.4408 km

Figure 7: Mustang Study Approach to Buoy
This is a picture taken from the test boat as the viewers were approaching a yellow colored

different colors were detected in both testing methods and both luminance conditions. It is important to note that the viewers were not given the color of the target beforehand and they were only told the buoy would be placed in front of them. The different color buoys were dropped in front of the viewers for only 2 trials at most. For 1 trial, each observer searched for each color on the water once. If the observers didn't detect the buoy during their trial, they were not given another chance to detect the buoy.

It is also important to note that the weather throughout this experiment was generally overcast conditions and partly cloudy with no wind or rain in the morning, but light wind and rain at night[30]. The general on-water conditions for each experiment can be seen in Figure 7 and were a control variable for the experiment.

The Fluorescent green color was clearly chosen as the most visible color for three of the four "on-water" tests as it could be seen from the furthest distance away. The red and yellow colors were consistently not as visible compared to the fluorescent colors as seen in Table 1, above. Red and yellow were consistently seen from the two shortest distances on average based on the table. Overall, the Mustang Survival study demonstrated that fluorescent colors need to be included in experimental design.

Not only were the colors important elements of the Mustang Survival experiment, but the controls and variables were important elements as well. Mustang Survival used the color of the target buoy as an independent variable and length of visibility as their dependent variable. Mustang controlled their experiment by keeping the buoy in the same place in the water by anchoring it down to the bottom, testing on days with the same weather conditions and water conditions, and testing in the same location every day.

Contrast is Important to Separate Color from its Background

The Seasonal-Variation Study was conducted in 2007 by Mary Lynn Buonarosa and James R. Sayer. Their study was a naturalistic daytime field study conducted to investigate the effects of garment color, the amount of background material, driver age, and season on the conspicuity of high-visibility garments. The experiment was conducted by having 24 older drivers (61-89 years of age) and 12 younger drivers (19-30 years of age) drive the same vehicle over a 29 km route with the task of detecting pedestrians wearing high-visibility safety garments[31]. The drivers in this experiment were independent variables as the researchers used old and young drivers to see if color detection was influenced by age. The route and cars the drivers drove were major control variables that helped the researchers limit a lot of unnecessary error. For that reason, it is important that the viewing platforms for experimental observers remain constant throughout the experiment. That means having the location of the buoy remain the same and the height of the eye being the same for each observer during each trial.

The experiment was to be done without knowing where on the road the pedestrians would be located or how many total pedestrians there were on the route. Two garments that were being detected had yellow-green fluorescent material and the other two had fluorescent red-orange material. The two different garment types were vests and jackets and they all had retro-reflective trim on them[31]. The garment types and the color of the garments were the researchers' main independent variables, in addition to the season.

In order to determine the distance from which the driver was able to detect a pedestrian, a researcher sat in the passenger seat of the car and marked on a GPS where the driver thought they saw a pedestrian. Since the pedestrians were already marked on the GPS system the researchers were able to use the technology to calculate the distance, in km, from which the pedestrian was detected[31]. This is another significant study that used GPS systems to determine the detection distance for each colored object.

In the results sections of the paper the garment type, effect of season, and effect of color were noted. Based on the results the drivers were able to detect all pedestrians at 71 m further when the subjects were wearing jackets instead of vests. The researchers noted that detection distances for fluorescent yellow-green and fluorescent orange did not vary much. However, they did note that yellow-green was detected better in the fall and red-orange was detected better in the summer[31].

Figure 8 helps illustrate the effect the

Figure 8: Fluorescent colored vests depicted in summer (above) and fall (below) backgrounds at the same location[31].

background has in relation to the color of the vest or jacket. The conclusion is that the greater the contrast between the background and the color of the vest, the easier it is to be detected. Although this study was not conducted on the water, the relationship between color and background is a factor to be considered in experimental design.

Yellow and Green are Detected More Easily Through Night Vision Goggles

In 2004, an experiment was conducted by 5 researchers to see if a P45 White Phosphor background would alleviate some of the problems caused by the P43 Green Phosphor background of night vision goggles when detecting three different colored symbols of green, yellow, and red[32]. In the experiment, the researchers used 12 volunteers all with normal or correct-to-normal visual acuity and normal color vision to test the detectability of the different symbols with two different backgrounds. The viewers or volunteers in this experiment were one of the control variables in the researcher's experimental design. The different colored symbols and backgrounds were presented on a 21-inch EDL CRT monitor and viewed by the viewers at a distance of 8 feet. The 8 foot distance and presentation monitor remained constant throughout the experiment[32].

The symbol colors were one of the input, or independent, variables of this experiment. The colors ranged from 1.025:1 to a 2:1 luminance contrast ratio. The backgrounds of P45 White Phosphor and P43 Green Phosphor were also input or independent variables for the experiment. Each color was presented on each background on the monitor for 500 ms (milliseconds)[32].

After viewing the colors of the same intensity on the different backgrounds the volunteers used keyboards to indicate whether they thought the color was green, yellow, or red. They rated their choices by using the 7,8 and 9 keys to indicate they were very sure, the 4, 5 and 6 keys to indicate they were somewhat sure, and the 1, 2 and 3 keys to indicate they were not sure about the color they indicated[32]. Color recognition was also a control variable for the experiment as the way the data was collected remained constant throughout the experiment.

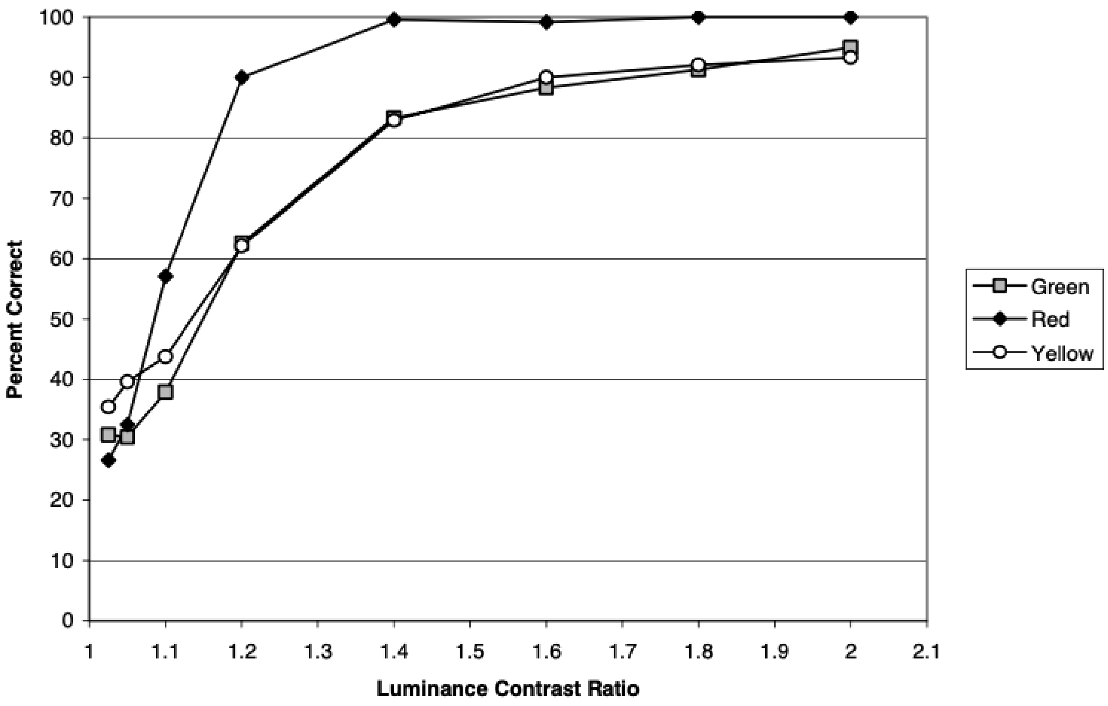


Figure 9: Interaction of symbol color and luminance contrast ratio[32]

The results were graphed Percent Correct vs Luminance Contrast Ratio and the yellow and green colors were detected at about 90-94% correctly, while the red symbol color was detected almost 100% correctly. These results can be found in Figure 9. Thus, it is important to include non-fluorescent red to the color palette for our experiment.

Analyzing Variables Used in Past Experiments

After finding reports, experiments, and studies discussing what colors are more visible in different weather conditions, the team created an excel sheet to show all the variables in each of the experiments or studies.

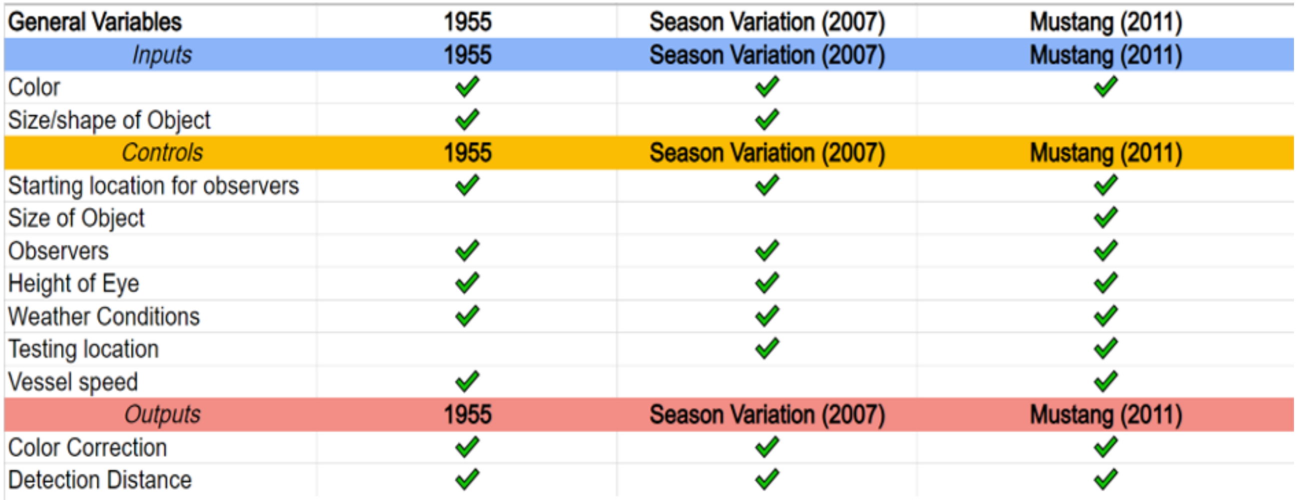
Each of the experiments the team analyzed tested different color palettes. The Mustang Survival Study tested the colors: fluorescent green, fluorescent orange, yellow, and red[30]. The 1955 study tested the red through yellow color range including both fluorescent and standard paints for each color[2]. The Season Variation study tested fluorescent yellow-green and fluorescent red-orange[31]. All of these studies/experiments reached the same conclusion: fluorescent colors were more conspicuous than non-fluorescent colors. Incorporating this conclusion into the team's color palette, we will use the fluorescent green-red color range. The colors (and their hex coordinates) the team will be testing are Indian Orange (FF4F00), Fluorescent Yellow (EDFF00), Fluorescent Yellow-Green (CCFF00), Fluorescent Green (8CFF00), Fluorescent Orange (FF8300), Fluorescent Red-Orange (FC4827), Fluorescent Pink (FF5AAC), Red (E03C31), and White (FFFFFF)[40]. We have incorporated the standard Red and White into our color palette to allow for baseline data from these colors compared to the fluorescent colors.

The amount of ambient light is dependent on the weather condition and time of the day. Each experiment the team analyzed tested in different ambient light conditions. The Mustang Survival On-Water Experiment placed a luminance photometer next to their target buoy to calculate the amount of ambient light for each test run[30]. The 1955 study tested in clear and favorable conditions, however they did not measure the amount of ambient light for each test run[2]. The Emergency Vehicle study analyzed information both during the day and at night. The impact of ambient light on an observer's visibility is vast. The report shows a significant decrease in visibility at night, without use of technology. In the Emergency Vehicle study, to identify people and objects, different technologies were used at night[39]. Some of these technologies used were retroreflective material and searchlights.

The detection distance is one of our dependent variables. The 1955 study, Mustang Survival in-lab testing, and Mustang Survival "On-Water Experiment" all measured visibility differently. The 1955 study was searching for the objects from an aircraft at a height of 700ft above sea level. Upon first detection, a stopwatch timer was started. Once the aircraft was directly above the object, the timer stopped. The detection distance was calculated based on the speed of the aircraft[2]. The "On-Water Experiment" from Mustang Survival was conducted similar to the 1955 study. A target buoy was placed in the water, however, the observers were only 8ft above sea level on a boat. The buoy's coordinates were calculated prior to the departure of the observers. The boat then approached the target buoy, the coordinates were then calculated for first detection by the observers. Using the change in longitude and latitude from the buoy to the boat, the distance from the boat to the buoy can be calculated using the circle distance formula. The circle distance formula is a simple conversion from degrees latitude and longitude to distance, incorporating the radius of the Earth[30]. Each experiment had their own version of calculating visibility and detection distance. The team will incorporate the method used by Mustang Survival to determine the detection distance. Calculating the coordinates of the boat and the buoy using GPS will give us a sufficiently accurate distance.

The first control variable analyzed is human perception. Human perception was a control variable in the 1955 study because all the observers were Coast Guard personnel with 20/20 vision[2]. The Mustang Survival experiment also took human perception into consideration, as they got observers from all different careers and backgrounds to collect their data. Their observers all had different vision, but were not color blind and

Table 2: Experimental variables from past experiments/studies



General Variables	1955	Season Variation (2007)	Mustang (2011)
Inputs	1955	Season Variation (2007)	Mustang (2011)
Color	✓	✓	✓
Size/shape of Object	✓	✓	
Controls	1955	Season Variation (2007)	Mustang (2011)
Starting location for observers	✓	✓	✓
Size of Object			✓
Observers	✓	✓	✓
Height of Eye	✓	✓	✓
Weather Conditions	✓	✓	✓
Testing location		✓	✓
Vessel speed	✓		✓
Outputs	1955	Season Variation (2007)	Mustang (2011)
Color Correction	✓	✓	✓
Detection Distance	✓	✓	✓

did not have any uncorrected vision defects[30]. In the proposed experiment, the observers should be Coast Guard search and rescue personnel with 20/20 vision and no color blindness or uncorrected vision defects.

The height of the eye was the next control variable analyzed. The height of the eye is defined as the height the observer is in comparison to the object. The height of the eye was controlled in the 1955 study as the plane flew at a constant 700ft above water[2]. The height of the eye was constant in the Mustang Survival study as the observers on the boat were at a constant 8ft above water[30]. We will control the height of the eye to a constant, minimizing the amount of standard error. For our helicopter portion of the experiment, the height of the eye will remain at 700ft above water. For the boat portion of the experiment, the height of the eye will remain at 8ft above water. Testing in a Beaufort scale 5, will result in some oscillation of the boat from the waves. However, this oscillation is minimal and will not result in skewed data. Therefore, the height of the eye will still be considered a control in the experiment.

Testing location is a control in all of the past experiments we analyze. The Mustang Survival experiment ran all of their On-Water tests in the British Columbia harbor[30]. The 1955 study controlled their location site to Long Island Sound, NY. To mitigate the amount of error from testing in multiple locations, our team will control the testing location[2]. Starting location was also controlled in both the Mustang Survival experiment and the 1955 study. Both had their observers begin their departure from the same distance away from the object they were detecting for each run, diminishing any error that could result from different starting locations. The starting location in our designed experiment will be controlled as well to allow each observer the same amount of distance to locate the buoy.

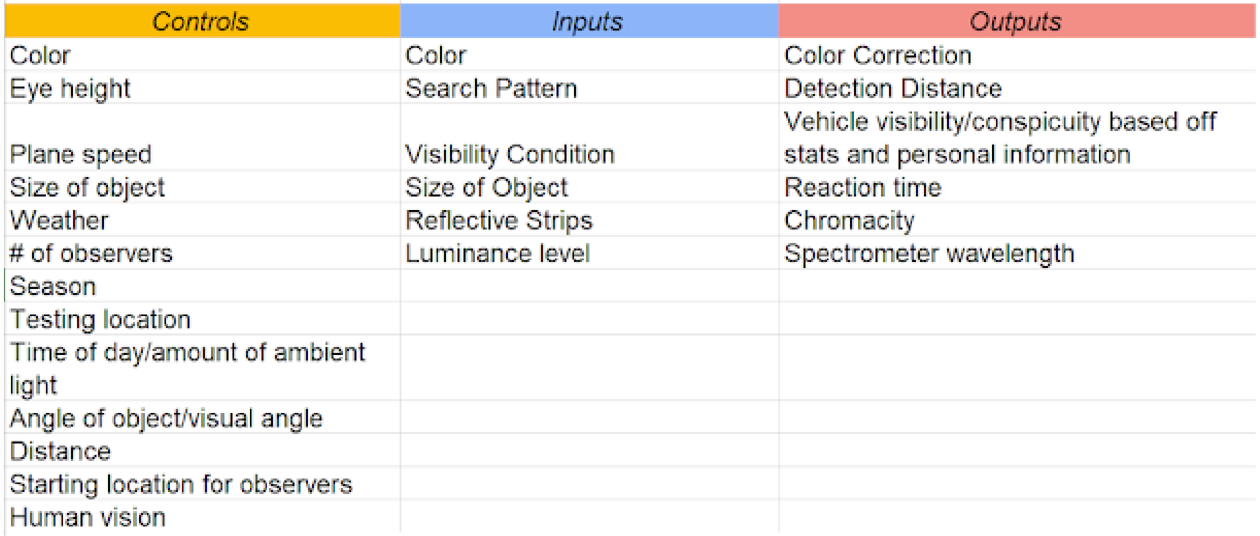
Speed of the vessel was controlled in both the Mustang Survival and the 1955 study. The boat was controlled at a constant 5-7 knots during each run in the Mustang Survival experiment[30]. The aircraft flew at a constant 160 knots for each run in the 1955 study. Keeping the speed of the vessel constant will decrease the amount of error between each run.

The size of the object was controlled in both the Mustang Survival and 1955 study. For the Mustang Survival experiment, the buoy size was controlled with an outer diameter of 26.1cm and their overall circumference of 81.9cm[30]. The 1955 study controlled the size of the object for each run. The 1955 study allowed each observer to conduct a run with all of the controlled objects. The 1955 study used small, medium, and large life rafts, human dummies, and 34in (86.36cm) diameter spheres. The team will also control the size of our object in our designed experiment to mitigate the sources of error from varying object sizes.

After combining all the variables into one Excel sheet, the variables were dissected into three parts: controls, inputs, and outputs. Referring to Table 3, each variable analyzed from the past experiments was classified into their respective part. Understanding these three topics proved how to properly develop an experiment accounting for all three factors.

Following the second step of the Experimental Design Process presented in the flowchart of Figure 5, the most important variables that affect visibility were determined. The independent variables are color of the object, while the dependent variables are detection distance and color correction variables. The most important control variables are: human perception, amount of ambient light, height

Table 3: Table of variables organized into controls, inputs, and outputs



Controls	*Inputs*	*Outputs*
Color	Color	Color Correction
Eye height	Search Pattern	Detection Distance
Plane speed	Visibility Condition	Vehicle visibility/conspicuity based off stats and personal information
Size of object	Size of Object	Reaction time
Weather	Reflective Strips	Chromacity
# of observers	Luminance level	Spectrometer wavelength
Season		
Testing location		
Time of day/amount of ambient light		
Angle of object/visual angle		
Distance		
Starting location for observers		
Human vision		

of the eye, testing location, starting location of observers, the speed of the vessel, and size of object. The independent, dependent, and control variables are further explained in the Experimental Design Protocol (see Supplementary Materials).

Coast Guard Search and Rescue Procedures and Technology

In order to develop a strong experiment, the team needed to understand the process of Search and Rescues. The research conducted identified different areas of focus for the US Coast Guard when performing a rescue. The purpose of interviewing Coast Guard personnel was to gain insight on search and rescue experience in relation to visibility of objects in the water.

During the team's visit to USCG Sector Southeast New England, Woods Hole in Falmouth, Massachusetts, a total of 20 interviews with Coast Guard personnel revealed the procedures and technology used during search and rescues. These interviews included experienced members in SAR from the Command Center, operators of 45ft cutter boats, operators of 110ft boats, and one helicopter crew. The interview questions (see Supplementary Materials) focused on what experienced personnel saw as important factors when performing a search and rescue.

In addition, the team conducted interviews via Zoom, FaceTime, and Microsoft Teams with other mariners in commercial boating including charter boat and cargo ship captains. The five mariners interviewed provided important insight on the visibility of colors on the water using human perception.

Fog is the Most Difficult Marine Condition to See in

Interviews have revealed how mariners use human perception to find objects in the water. Interviewees concluded that mariners believe the current Indian-Orange color is the most visible through any marine condition, and of those conditions, fog is deemed the most difficult in which to see. One mariner said that heavy rain could sometimes reduce visibility equivalent to that of a white out[33]. In these cases the rain would be falling faster than it could be wiped away from the windows. In these conditions he recommended bright yellow life jackets as they contrast better against the rainy conditions. Mariners agreed that at sea, height of the eye relative to the waves can greatly affect the detectability of the target. It's very easy to lose sight of an object when waves keep obstructing one's view. Mariners along with the Coast Guard, rely on technology and instruments to aid them in finding and detecting objects in the water. Like the Coast Guard, mariners use GPS, radar, forward looking infrared (FLIR), search lines, among other instruments when searching for objects.

One mariner we spoke to mentioned that the technology used helps find the general vicinity of the object but it comes down to human perception to locate it[34]. This mariner uses all hands on deck to scan the water for objects. That way smaller objects that may not always get picked up by the radar are seen by a crewmate. Another mariner interviewed described how once one of his crewmates locates an object or person in the water, everyone is responsible for maintaining eye contact while the pilot pulls towards it[35]. The mariners seemed to agree that fog and snow affect visibility the most. When piloting a boat, the snow often blows into one's eyes, blocking vision. Throughout these interviews, night vision goggles were found to be the instrument mariners use the most when searching at night. Some mariners perceive objects differently. After speaking with these mariners, we realized how both color and shape are crucial in SAR.

The roughness of weather condition and water (sea state) greatly impacts the ability to locate objects in the water.[34]

The team got the opportunity to speak with Eric Christensen who served 26 years in the Coast Guard in marine safety. Christensen has been the director of regulatory affairs and risk management at Passenger Vessel Associations for about 6 years and has worked as a traveling inspector for the Coast Guard for 9 years[36]. Over the years, he has inspected all types of lifesaving equipment that is required for vessels including commercial ships such as ferries, tankers, and cargo ships. He has also dealt with cruises, sightseeing vessels, private charter vessels, and many others. During our discussion, he mentioned that the reflective tape on life jackets tends to wear down, causing them to become and appear a dull gray[36]. This prevents life jackets from reflecting light, making them less detectable.

One interview conducted revealed the process of in-lab testing and on-water testing for one of the original color studies we researched done in 2001. Wendell Uglene, the manager for the Mustang Survival color study, discussed the variables chosen for this study. When conducting his initial research on past experiments, he found very little information on color in the marine environment[37]. Curiosity on conspicuity led to in-lab testing of colors. Uglene and his team measured fabric chromaticity. One factor Uglene did not consider was whether all the observers participating in the experiment had similar eyesight. A pre-screening on eyesight was not conducted beforehand. Observers were only checked to see if they were colorblind or had any uncorrected visual defects[30]. Observers who were not colorblind or had no uncorrected visual defects were allowed to be used as test subjects. Uglene did not consider using more observers for each subject; this would have involved gaining access to a bigger boat. Many crab fishermen went to Uglene suggesting neon pink, which is easier to detect through fog, as a color to use since crab fishermen use that color for their buoys. Uglene mentioned that contrast heavily affects whether an object is spotted from its background[37]. When performing the on-water portion of the experiment, Uglene measured the amount of sunlight that was shining on and around the buoy. He wanted to keep the luminance level constant; to do so, he changed the starting position of the boat so that the sun was always to the back of the observers. As the luminance directly affects the visibility of objects the lux level needs to be kept within a constant range for each test.

Wave Conditions Affect Detectability of Objects in the Water

We've also gained insight on search and rescues through interviews with Coast Guard personnel. We found that January has some of the worst weather conditions. The team had the opportunity to go out on a 45 ft cutter and be a part of a mock man-overboard drill. Through this, we were able to gain an understanding of how challenging it is to spot an object or person in the water. The conditions this particular day were windy and rainy causing the condition of the waves to be harsh. We observed that one minute you could have eyes on the victim and the next the victim would be behind a wave. The height of the waves can easily hide the visibility of an object or person in the blink of an eye.

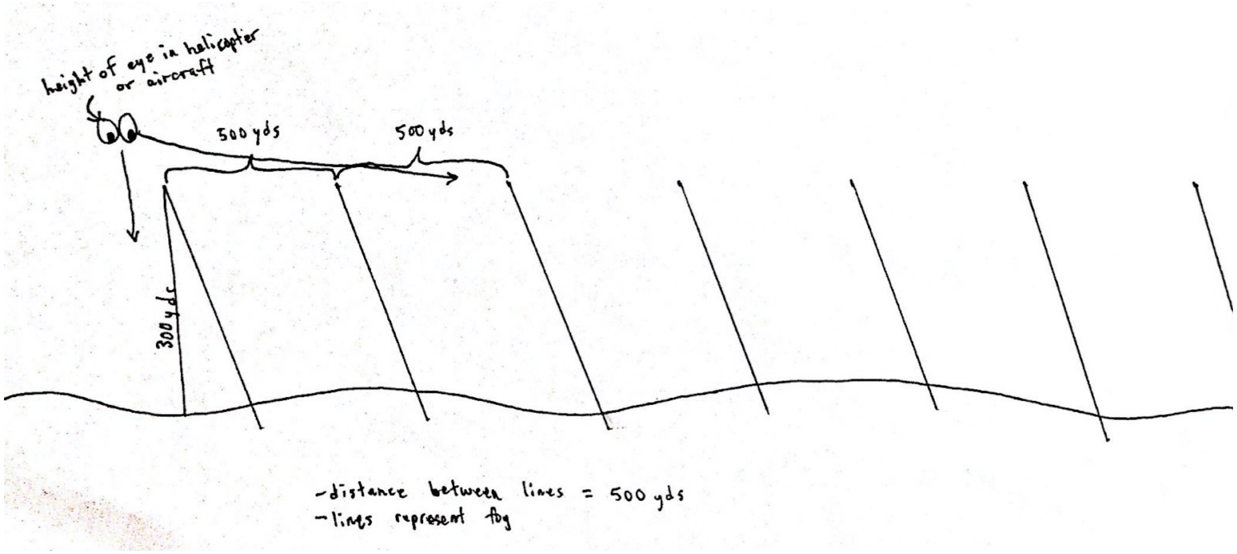


Figure 10: Fog Layer Diagram from LT Kyle[24]

When conducting search and rescues, the Coast Guard has different tactics when searching at night versus during the day. At night, Coast Guard members look for light reflecting off an object more than during the day. Retro-reflective strips on lifejackets are very heavily relied on for on-water search and rescues at night[38]. However, during the day, color is more conspicuous enabling them to look for color[38]. From speaking to some of the crewmates who were on board with us, glare from the sun hampers search and rescues, even if members come prepared with sunglasses[38]. Especially during the summer when it is sunny much of the time, sun glare can affect the visibility of survivors on the water. Dusk and dawn, when the sun is positioned directly at eye level becomes the worst angle for visibility. Upon further discussion, snow is another condition that is difficult to work in[38]. When snow falls on and around a lake or ocean, it creates a blanket of white. This causes light to reflect off the snow, limiting visibility.

After speaking with a U.S. Coast Guard member who is a Lieutenant at USCG Air Station Cape Cod, high elevation makes searches in adverse marine conditions easier[24]. For instance, when conducting a search and rescue in dense fog from a boat, everyone searching from water level is directly in the fog. However, with fog, searching from the air creates fewer issues as the distance of fog needed to search through is shorter, as visualized in Figure 10. Comparing the notes from speaking with Coast Guard personnel at the command center and at USCG Air Station Cape Cod, boat search and rescue relies heavily on technology to locate a stranded victim or object. Air search and rescue relies more on human perception.

Search and Rescue Operations Determines the Search Strategy

The Command Center's main purpose in Search and Rescue (SAR) is to deploy units and make sure they are searching in a way that greatly increases the chances of rescue. The command center operates by reacting to communications and distress calls within its area. Upon receiving information and the location of the distress call the Command Center is able to use SAROPS, a predictive technology to plan search patterns that increase the chance of members spotting survivors. To do this they take data on wind speed and current and use it to plot different position/time models in order to increase the chance that the Coast Guard can accurately locate survivors[38].

Specifically, in colder weather the time it takes the Coast Guard to reach survivors is key. "Minimizing the time required to achieve the maximum possible POS (probability of survival) with the available resources is very important to the saving of lives since the prospects for continued survival following a distress incident often decline rapidly with the passage of time."[41] In colder weather people can enter a state of hypothermia within 1 hour of entering the water. This timeframe is further cut by the time it takes for Coast Guard units to launch. The success of a SAR mission depends on the speed with which the operation is planned/carried out. The closer a boater is to shore when they go overboard the more likely they are to be found by the Coast Guard.

According to the SAR manual, more than 95 percent of all Coast Guard SAR cases occur within 20 nautical miles of the shore[41]. Radios go out 20 nautical miles typically. The command center uses radio position technology to track the last known location of survivors within 20 nautical miles of shore. After a location of the stranded victim is obtained, the command center utilizes a computer program called SAROPS to find survivors[38].

SAROPS

Comprehensive planning of SAR response tasks is essential, especially when the location of the distress situation is unknown and the survivors move due to wind and water currents[41]. SAROPS is a software that uses the color, size, and position of objects, to determine the most efficient location to search for the victim. This is based on on-site measurements of the wind, tides, and the last known location. SAROPS addressed that wind and tide affect objects differently depending on how much of the object is sticking out of the water[38]. This is important because a person wearing a personal floatation device (PFD) will drift more than a person without a PFD. After simulating multiple objects the Coast Guard is able to determine the effect of the current and wind, and choose a suitable search pattern.

SAROPS uses a mathematical algorithm to determine the sweeping distance of their search patterns[38].

During our trip to the USCG Sector Southeast New England, Woods Hole, a SAR officer stated that the SAROPS program considers color contrast in the calculation of search patterns. Orange is considered high contrast in the daytime whereas anything else is considered low contrast[38]. At night, anything with a visible reflective strip is noted as high contrast and anything else is tagged as low contrast. Colors must be easy to spot in various conditions on the water since search boats and helicopters are given limited information on the location of the stranded victims.

Conclusion

The literature review of past experiments identified the principal variables that affect visibility and how the variables were selected and used in the various experiments. Based on this information, the team designed an experiment including each of these variables to study the visibility of colored objects under adverse conditions in a marine environment.

Interviews with mariners identified key factors that affect visibility and detectability when searching for objects in the water, which include weather condition, sea condition, technology in use, and color of the target object. Interviews with Coast Guard personnel revealed the search and rescue procedures and technology used that aids the Coast Guard in those procedures.

Our experimental design expands upon the conclusions drawn from the visibility test conducted by the Coast Guard in 1955 that led to Indian Orange being deemed as the best color for lifesaving equipment. The 1955 experiment conducted visibility tests only in ideal clear conditions and never accounted for the adverse conditions in which SAR missions are often conducted. The proposed experiment tests the visibility of colors in adverse weather conditions such as rain, fog, and bright sunlight. Another variable we factored into our experiment was the sea state as measured by the Beaufort Scale. We designed our experiment to test in sea conditions with and without white caps, to determine which colors are easier to detect in rough sea conditions. Upon completion, this experiment will enable the Coast Guard to determine if the current Indian-Orange color is more visible than other colors in the marine environment.

Future Additions to Incorporate into the Experimental Design

1. The Coast Guard should develop an app to implement the User Segment of the GPS software which will greatly reduce error in determining the detection distances of the buoy and the correct color of the buoy.

The User Segment part of the Coast Guard's GPS software consists of receivers, processors, and antennas that allow land, sea, or airborne operators to receive the GPS satellite broadcasts and compute their precise position, velocity, and time[42]. As shown in the flowchart in Figure 11, the GPS software will allow observers to click on the color first detected and a pin will be dropped for buoy detection. If the observer identifies the correct color upon initial detection of the buoy, the initial object detection pin will be noted as accounting for correct color detection as well. If the observer does not identify the correct color initially, a pin will still be dropped for detection of the object. However, the observer will then be prompted to continue locating the buoy until the correct color is detected. When the correct color is clicked a pin will be dropped and the observer will no longer be prompted to drop any pins on the GPS. If the observer incorrectly identifies the color, a pin will not be dropped and will be prompted to choose the correct color will pop up on screen again. This will happen until the observer chooses the correct color. If the buoy is never identified by the observer, no pin will be dropped for the detection.

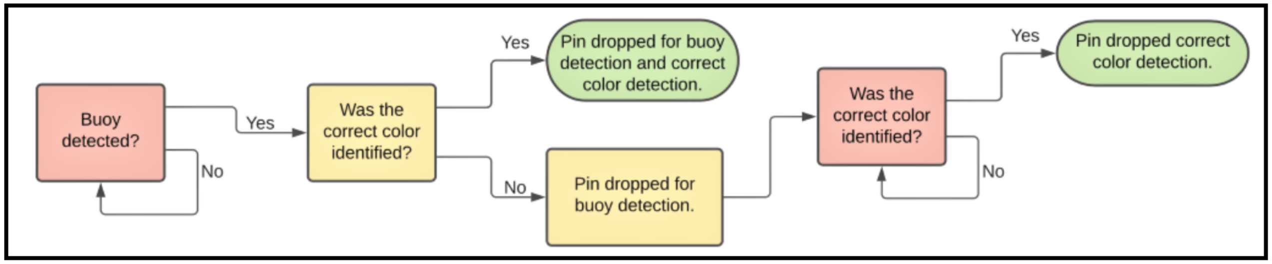


Figure 11: GPS Application Flowchart

2. Night vision goggles (NVGs) should be used in a future experiment to test which color is most visible through NVGs at night.

After researching how night vision technology works, we suspect colors that reflect more light will be more visible through NVGs. We recommend testing NVGs ability to detect different colors in a closed room indoors with a lux level of 100-500 lux. This is recommended because it will allow for a totally controlled experiment to be conducted without interference from the surrounding environment. Testing NVGs on the water was considered, but too many factors of error would be induced as the surrounding environment out on the water is not something that can be controlled. The objective of this experiment is to see which colors appear as a brighter green pigment through the NVG phosphor screen. Nine 30-inch colored buoys will be placed in a row 50 yards away from the observers. Fifty yards was chosen because the maximum range for NVGs is 200 yards. 50 yards is not close enough to the observers where they can physically see them without NVGs and it is not out of the 200 yard range. Each buoy will be colored using the colors of our color palette and numbered 1-9. Observers would be members from the Coast Guard with corrected and uncorrected 20/20 vision. Observers will be asked to look at all nine buoys at once and be asked to pick out the numbered buoy that shows up best through the NVGs and tell the researcher which number they chose. The color with the most votes to be specified as easiest to see would be declared the most visible color. Figure 12 shows the physical set up for this experiment inside a closed room. Buoys numbered 1-9 in the image are colored with the colors from our color palette. A future experiment conducting a test following a similar procedure can help give a safer color to wear on the water during all adverse marine conditions.

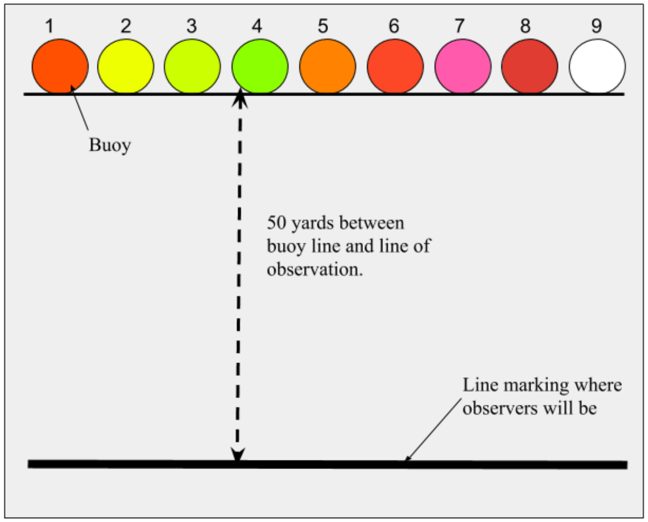


Figure 12: Experimental Set Up for NVG Testing

3. Testing the difference of these types of strips and analyzing which is more visible at night could be incorporated into the current lifesaving equipment.

Understanding and incorporating which reflective strip is more visible in low ambient conditions would allow objects and people in the water to be located more quickly. The use of reflective strips was outside the scope of our study. However, retroreflective strips are already a requirement on certain US Coast Guard lifesaving equipment. Retroreflective strips increase the visibility of an object during low ambient light conditions. Analyzing the Emergency Vehicle study showed that different variations of strips (circular, triangular, and prism) can enhance the visibility of an object. The retroreflective efficiency ranges from 7-14% for circular, 32% for triangular, and up to 58% for prism[31]. Just because the retroreflective efficiency is higher for a material, does not imply that it is “better.”

4. Testing the top few most visible colors from our experimental design for detection using different search patterns in various weather and sea conditions would supplement the proposed experiment.

Testing the colors defined as “most visible” for their detectability using the search patterns the Coast Guard regularly incorporates into search and rescue missions can verify the results of the experiment. Steering or flying the vessels directly towards the buoy could result in less reliable results than designing an experiment steering or flying the vessel using the Coast Guard search patterns. The team advises using an unanchored buoy, allowing it to move with the current, causing the observers to use a search pattern to locate the buoy.

5. Combinations of colors should be tested for their visibility on the water.

Combinations of colors on lifesaving equipment could maximize detectability of the equipment. The goal of our experiment was to provide a way to identify the most visible color in adverse marine conditions. Since our focus was on how to determine the singular most visible color, we did not look into testing color combinations in adverse marine conditions. In a future experiment, analyzing how easily a combination of the most visible colors from the results of our experiment would be detected on the water could prove new color combinations should be incorporated into the lifesaving equipment. A combination of the most visible color and a contrasting less visible color on a buoy will affect the detectability. Contrasting colors on a single buoy could allow for the buoy to stand out in more adverse weather conditions than a single colored buoy.

6. Faded colors should be tested for their visibility in adverse weather conditions.

Our project scope was to determine the most visible color in adverse marine conditions, so the color palette we are including in our experimental design does not include the faded colors because they are not the most visible. Testing faded color for their visibility on the water is important because it would give a scope of how effective the color truly is for visibility, as many mariners do not buy brand new colored life vests every year.

7. Testing in different backgrounds will show which colors contrast better in certain areas of the water, which could prove a different color to be most visible on the water.

This is most relevant to searching on the water by boat. For future testing, an experiment conducted with different backgrounds could change the conclusion of our results. Through our literature reviews and interviews a common theme that we came across was that colors that contrast with its background the most are easiest to see. Given the timeframe we had to design this experiment, it would have been very difficult to account for different backgrounds (such as trees, a rocky cliff, or a city). In our experiment the background we were trying to find colors to contrast with white caps in a rough sea, the glare from the sun, heavy rain, and fog. The most visible color from our experiment could change based on the background the color is being compared to. The further the observer is from the buoy, the lower the angle of view is onto the object in the water (see Supplementary Materials). Eventually, as an observer moves far enough away from the buoy, they will be looking at a degree of almost 0 which is parallel to the horizon or shore. That is why testing should be done accounting for different backgrounds.

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