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Color, Light, and Depth: Investigating Fish Camouflage in a Warming Marine Environment

A Thesis in the Department of Mathematics and Computer Science

by

Katerina Poulathas

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Abstract

Climate change is altering all ecosystems, displaying negative effects on our world as a whole. The effects of climate change on light penetration through the ocean may seem trivial, but it could potentially have drastic effects on all marine life. This thesis explores how changes in ocean temperature due to climate change may affect underwater light penetration, and therefore disrupt survival techniques of fish such as coloration and camouflage. Changes in light and color penetration could have a significant impact on fish and marine species that rely on the ocean's depth to survive.

Changes in geographical locations of fish over time are more widely studied than changes in the depths at which they frequent. Along with examining the effects of climate change on light penetration in the open ocean, this thesis also studies the visibility of fish coloration at various depths. With the use of a modern analytical framework, as well as data obtained from *FishBase*, this study was able to visualize how environmental factors such as water temperature and light attenuation might alter the effectiveness of color-based camouflage in fish. It is the goal of this study to provide insight on how climate change could disrupt and alter species' reliance on deep-sea environments.

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Introduction

Background and Motivation

The physics and mathematics of color is an incredibly interesting topic, especially when studied in different mediums. In water, the familiar properties of light and color behave in unexpected ways. Furthermore, factors such as depth, water clarity, and the angle of the sun all influence how light travels and affect how color is perceived in aquatic environments like the open ocean. As these factors shift, the visibility of both light and color can change dramatically.

Like most other ecosystems on the planet, marine environments are undergoing significant changes due to climate change. One major impact is the migration of fish species in response to rising ocean temperatures. Marine ecologist Erin Spencer explains that extreme ocean warming events have become more frequent and severe, with the average water temperature increasing by nearly one degree Celsius since the start of the 20th century. Although this change may seem small, it has already had a profound effect on marine life. When faced with an increase in water temperature, fish typically have three options: to adapt, move, or die. For example, Summer Flounder were tracked, and it has been concluded that they migrated approximately 70 miles further northward due to unbearable temperatures. Not only does a rise in temperature affect the ecosystem that flounder belongs to, but it also negatively affects the fisheries that relied on the flounder (Spencer, 2023).

Although the latitudinal locations of fish are widely studied, their longitudinal locations are generally overlooked. Changes in the depth of fish due to the climate could be critical in understanding how fish adapt to environmental changes. Furthermore, increased temperatures also lead to changes in light visibility beneath the ocean's surface. Such changes begs the need

for future research to be done on marine organisms and how they adapt due to a change in visibility underwater due to climate change.

As color, not just light overall, is important to aspects of fish ecology such as camouflage, how these changes could depend on color, not just light overall, is important to understand. Particularly as species relocate into new areas of different light conditions. This uncertainty motivates the need for further research into the interaction between light, color, and marine life under the effects of climate change.

Research Objectives

This thesis aims to provide explanations to a wide range of topics related to light and color visibility below the ocean's surface. First, a comprehensive summary of color and depths of fish will be generated using data creation and analysis in R (a useful coding language). The results of this data analysis will show how the coloration of marine species correlates with their typical depth ranges. This will aid in establishing visible and quantitative patterns showing how different colors are visible (or invisible) at various depths. By analyzing the compiled data, this research will explore how the visibility of certain colors changes with increasing depth. Special attention will be given to understanding which colors are visible or invisible at specific depths.

Along with finding a relationship between the color of fish and the depths at which they frequent, this thesis also aims to examine the effects of climate change on water clarity and light penetration. As ocean conditions are affected due to climate change, water clarity and light transmission are also impacted. A major objective of this thesis will focus on understanding how such changes may alter color visibility in marine environments over time.

Finally, this thesis will analyze longitudinal fish migration patterns in response to climate change. Using an interactive interface developed in R, potential adaptations in fish migration trends due to an increase in ocean temperature will be visualized. The results from this user-friendly application will provide insights into how changing environmental conditions may affect the depths at which different species of fish frequent.

Through the course of this research, this thesis seeks to bridge the fields of marine biology, mathematics, and computer science to better understand how light, color, and marine life are interconnected.

Background

The Physics of Light and Color

Fundamentals of Light and Color

In order to investigate the effects of climate change on the visibility of color in the ocean, it is necessary to first understand the physics of light and color. Our modern understanding of light and color has evolved significantly over the centuries. Original theories were introduced by the Greek Philosopher Aristotle. His early conjectures led to experimentations conducted by Sir Isaac Newton. Newton's research eventually laid the foundation for our current understanding of the electromagnetic spectrum (The Science of Color, 1970).

In *Introduction to Light: The Physics of Light, Vision, and Color*, Gary Waldman lays a detailed foundation for both the origins and modern understanding of the physics of light. As stated previously, initial theories of light can be traced back to Aristotle. He believed that colors were the product of both light and complete darkness that were influenced by the four elements: water, earth, fire, and air. His theory was widely believed and remained unchallenged for over twenty centuries. In the early 1600s, however, Sir Isaac Newton conducted experiments that proved Aristotle's theories to be false. Utilizing glass prisms to conduct his experiments, Newton demonstrated how light from the sun can be separated into different colors. Now, we are able to deduce that these colors correspond to the colors that are widely accepted as the "colors of the rainbow": red, orange, yellow, green, blue, indigo, and violet.

While Newton's experiments were considered to be a scientific breakthrough, he merely scratched the surface of the physics of light and color. Regardless, his findings were able to pave the way for modern studies on the electromagnetic spectrum and how light is a form of electromagnetic energy that travels in waves of varying lengths (The Science of Color, 1970).

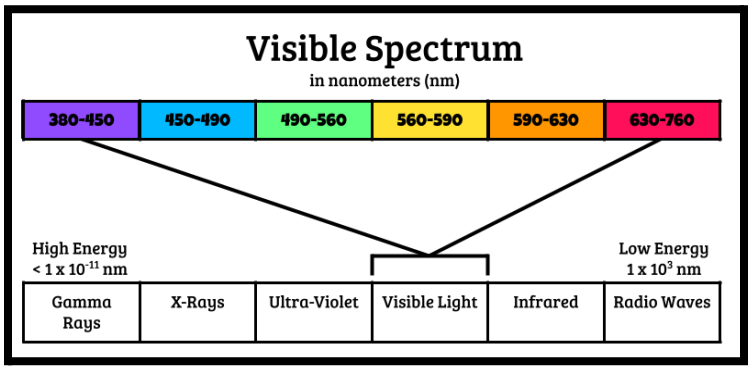
The Electromagnetic Spectrum

In scientific terms, light is defined as electromagnetic radiation that is detectable by the human eye. This radiation can be explained using the electromagnetic spectrum, which includes a wide range of wavelengths, typically measured in nanometers (nm). It ranges from less than 1 x 10^{-11} nm to 1 x 10^{3} nm, with shorter wavelengths corresponding to higher energies, and longer wavelengths corresponding to lower energies. Within this spectrum, there are seven distinct classifications: gamma rays, x-rays, ultraviolet radiation, visible light, infrared radiation, microwaves, and radio waves (Stark, 2025).

The portion of the electromagnetic spectrum ranging from approximately 380 nm to 760 nm is referred to as the "visible" part. This is due to the fact that it contains wavelengths of light that can be seen by the human eye (Waldman, 1983).

Figure 1

Electromagnetic Spectrum, Highlighting the Visible Spectrum



Note. The electromagnetic spectrum ranges from wavelengths of less than 1 x 10^{-11} nm to 1 x 10^{3} nm. Shorter wavelengths correspond to higher energies, while longer wavelengths correspond to lower energies. The sections of the electromagnetic spectrum is often divided into six common

categories. Ranging from highest to lowest energies, these include gamma rays, x-rays, ultra-violet, visible light, infrared, and radio waves.

Table 1

Colors and Their Corresponding Light Wavelengths

Wavelength Range (nm)	Color
380 – 450	Violet
450 – 490	Blue
490 – 560	Green
560 – 590	Yellow
590 – 630	Orange
630 – 760	Red

Note. Wavelength ranges in nanometers (nm) represent approximate values for visible light. Information adapted from *Introduction to Light: The Physics of Light, Vision, and Color* by Gary Waldman (1983).

The visible light spectrum can be considered as an additive color system, which describes how light produces color. In an additive color system, as with light, when all wavelengths of light are combined, they produce white light. In this system, there are said to be three primary colors that can be seen by the human eye: red, green and blue. There is another color system, known as the subtractive color system, that refers to how colors such as dyes or pigments interact with one another when light is being reflected off of them. This system differs from the additive color system because in this case, when all the colors are combined, a dull, dark color is produced. Similar to before, there are many factors that are at play in each of these color

systems, but it can be simplified to state that the primary colors of this system are red, yellow, and blue. One fact that is true for both color systems is that the primary colors of each can be combined in unique and specific ways to create every other color in their respective perceived color systems (The Science of Color, 1970). More detail on the many nuances highlighted in this section on perceived color will be further covered and explained in the following sections.

Modeling Color with Color Theory

The subtleties of color theory and color models are not always addressed in scientific papers, however, it is important to cover them for this thesis, as they pertains widely to the information presented. In order to understand color, it is helpful to understand color theory so that terms used to describe colors can be explained and described well. I will explain colors' hue, saturation, and brightness, which comprise one way to model perceived color, further on in this section.

Color Theory contains many ideas and knowledge that has been developing and evolving over the centuries. As G.A. Agoston (1987) explains in *Color Theory and Its Application in Art and Design*, our understanding of color is ever changing, as it is influenced by fields such as physics, biology, and psychology, where new knowledge is frequently gained. Depending on the context, color can refer to many different things. It can be defined as the light absorbed or reflected off of an object, the inherent physical property of a material, or even a perceptual experience influenced by lighting and the observers' visual system. Ultimately, color theory forces us to ask the question: is color the intrinsic property of an object, or is it merely a result of light interacting with the object and how it is perceived by the eye?

In order to understand and answer this question, it is first necessary to understand color, as it is perceived by humans. There are several ways in which a color can be characterized. In one widely-used and helpful model, there are three properties of perceived color that are key: hue, saturation, and brightness.

Hue, saturation, and brightness can only be described if it is first understood that they are a product of how the viewer perceives them. In the scientific world, the visible spectrum is one way to describe colors, as it attributes each to a wavelength.

Hue refers to the dominant wavelength of color that is perceived. It can be thought of as the base color of a perceived color. Hues are commonly identified as red, orange, yellow, etc. While humans can distinguish many hues, there are four that are important and referred to as *unitary* hues. Such hues include red, yellow, blue, and green. These are known as unitary hues because they can not be created by mixing or combining any other colors. Furthermore, all other hues in the visual spectrum are mixtures of these four hues. While hue does not necessarily refer to a single color system, it is necessary to understand that it is most closely linked to the additive color system.

Saturation is used to describe how intense or pure a hue seems, or the predominance of a single hue present within a color. For instance, a red-colored fish would be considered to be more saturated in color than a pink-colored fish because pink contains red hues, as well as all other hues necessary to create white light. The addition of all these other wavelengths reduce the intensity of red, diminishing its saturation.

Brightness depends on the intensity of light or light reflected off of an object. As the intensity of light on a surface increases, it can also be stated that perceived brightness increases. Colors may appear less bright, or dimmer, when there is less light present to illuminate an

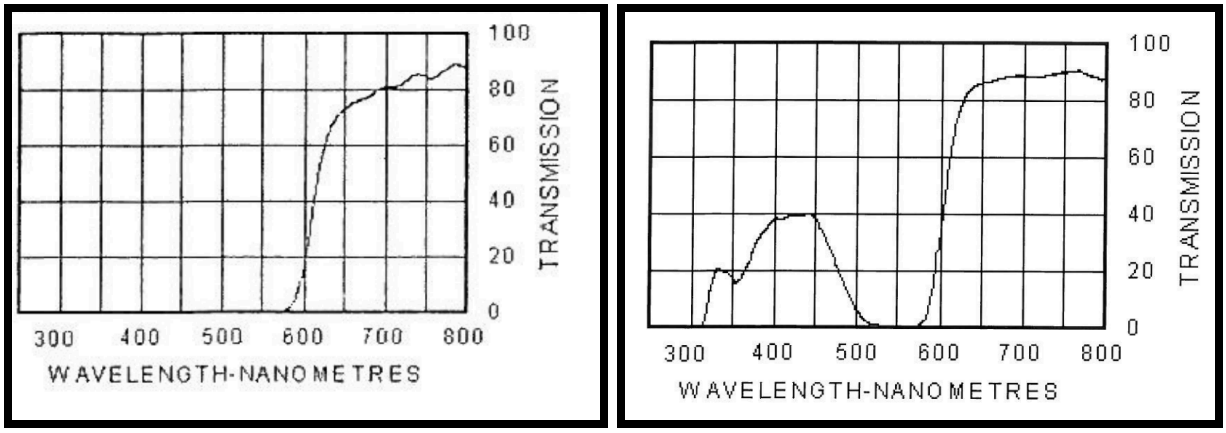
object's color or when the color itself absorbs more light. Brightness is a subjective quality of color, as it is shaped by both the external and internal factors of lighting and our visual perception. Although it is subjective, brightness is important to this research because it is something that both humans and fish perceive.

Colors that are produced by a single wavelength of light are referred to as monochromatic, or spectral colors, and they have maximum saturation. Furthermore, colors that are a product of a combination of two or more wavelengths may appear less saturated than monochromatic light, or even as saturated colors of a different hue. Additionally, hues and saturation of colors can be reduced as additional wavelengths of light are introduced. This in turn also lowers the saturation (Agoston 1987).

It is also important to understand that color perception, both on the color spectrum of the ambient illumination and on the object and how it reflects or absorbs light. When striking a surface, certain wavelengths of light are absorbed, while others are reflected back to the eye as the colors we see. Many plants, for example, appear green due to their special pigment, chlorophyll, which reflects green light and absorbs other wavelengths. While reflecting the green light that humans are able to perceive, plants also absorb all other wavelengths. Chlorophyll is then able to convert the absorbed light into energy in the process of photosynthesis. The green coloration of most plants is an important factor that not only helps them survive, but it also supporst entire ecosystems (Che, 2023).

Figure 2

Light transmitted (Y%) for Red and Bright Pink Wavelengths



Note. The above information is derived from Lee Filter's color filters information page. Lee Filters includes light transmitted wavelengths for a large collection of color filters used in commerce. The left graph depicts the wavelength-transmission spectrum for a red filter, while the right graph depicts the wavelength-transmission spectrum for a bright pink filter. The red-wavelength graph shows one peak-interval of transmission at around the 700-800 nm range. The bright-pink-wavelengths graph shows two relative peaks. The first one around 400-450 nm, and the second around 650-800 nm. While they both contain peaks in the portion of the graph corresponding to red light, the bright pink graph shows an additional peak, showing that it is not a pure hue and is less saturated as pure red because it contains a mix of other hues such as violet (Arbor Scientific, n.d.).

The Physics of Light and Color Underwater

While conducting research on a controlled environment, results can usually be easily investigated. The same thing can not be said when studying underwater environments. In a controlled state, the effect of water on light and color can be easily investigated. In the open ocean, however, there are many factors that must be taken into account. Such factors include salinity, temperature, plankton, and other floating particles.

The cause of the blue appearance of the ocean has been debated over centuries. Historically, the color was thought to have been a result of the sky's reflection, which was a theory introduced by Lord Rayleigh. After years of speculation, Soviet scientist Vasily Shuleikin concluded that the ocean's color was a result of the physical properties of water itself. In pure water, where H_2O is the only influencing molecule, absorption measurements, which refer to how much light is absorbed by a specific medium, can be easily experimented upon. In this case, the absorption measurements reveal that blue light has a much lower absorption rate than red light. This allows blue wavelengths to penetrate deeper.

Theories attempting to explain why certain colors are able to penetrate deeper in water than other colors are common. One such theory used energy and power to try to answer this question. While there are many different sources of light, the one that is most significant while studying underwater environments is the sun. When producing light, the sun emits wavelengths of all different energies. Relative spectral power distribution curves were used to try to understand why certain wavelengths penetrate deeper. Results from these curves showed that the sun emits more overall power at longer wavelengths and less power at shorter ones. This would mean that colors such as green, blue, and violet wavelengths would penetrate deeper than red, orange, and yellow wavelengths, as their powers are higher (Agoston, 1987).

Although the theory stating that violet light penetrates the deepest in water seems plausible, it is incorrect. Studies have shown that blue light is able to penetrate deepest in the water. While violet light may have a shorter wavelength with higher energy, it is scattered more readily in water. This ultimately limits its depth of penetration. Russian physicist Vasily Shuleikin explored this further and attributed the phenomenon to molecular vibrations. Specifically, the O–H bonds in water molecules vibrate in ways that selectively absorb certain

wavelengths. The vibrations move in a certain way, allowing some wavelengths (in particular, those nearest the resonant frequencies of these vibrations) to be absorbed more than others. Longer wavelengths, attributing to red and infrared light, are highly absorbed due to the propagation of the molecular vibrations. Furthermore, they can transfer their energy into these vibrations and are almost entirely absorbed. The frequency of blue light wavelengths, on the other hand, seldom aligns with these vibrations, allowing them to penetrate deeper into the water column, as they are absorbed far less (Dickey et al., 2011).

Light scattering is also affected by various physical properties in the water and can be modeled using the equation for molecular Brillouin (MB) scattering that describes the molecular vibrations:

$$\frac{\omega_{MB}}{\omega_0} = 2n * \frac{sin(\frac{\theta}{2})vs}{c} \quad (1)$$

and the equation for MB frequency shifts (ω) is:

$$\omega = \omega_0 \pm \omega MB \quad (2)$$

and n represents the refractive index of water, ω_0 represents the frequency of the incident light, θ represents the scattering angle, *vs* represents the speed of sound in water, and *c* represents the speed of light in a vacuum. In pure water, the backscattering frequency is typically around 7.5 GHz.

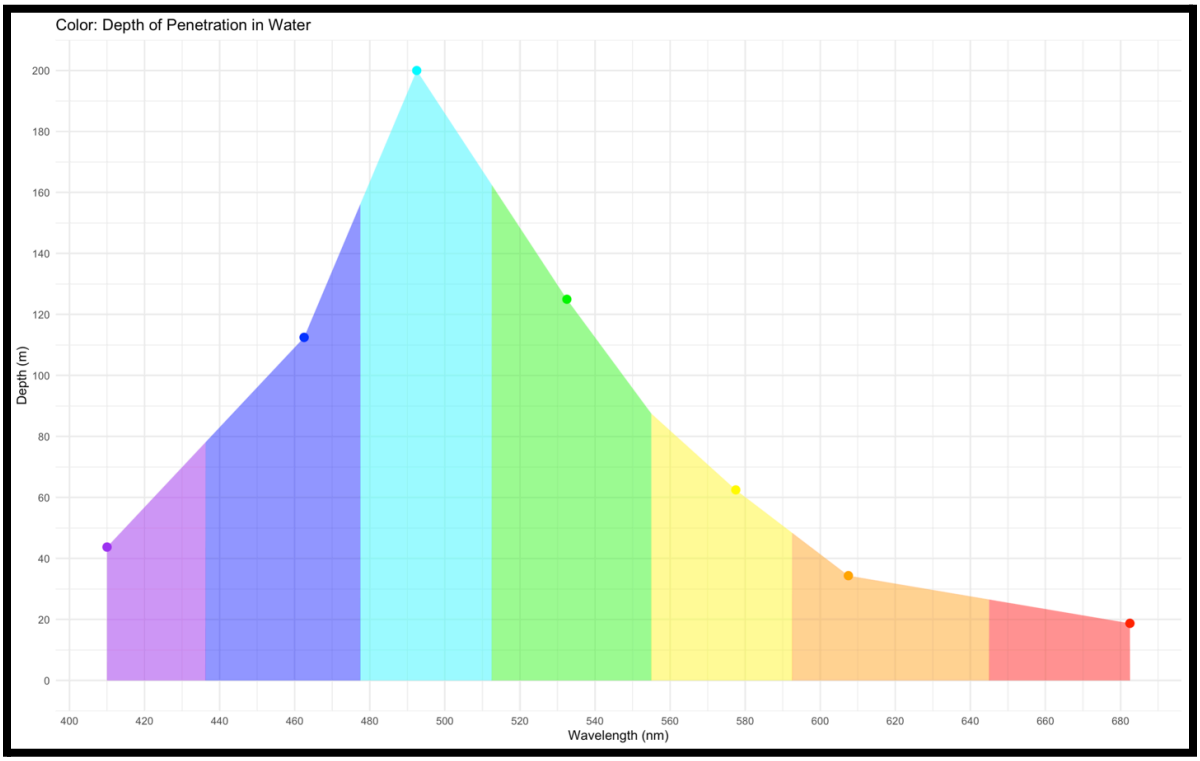
As stated before, there are many factors that are at play when studying the color of the ocean and the amount of light being transmitted through it. An increase in turbidity as well as organic and inorganic floating particles in the water can change the perceived hue of the water, ultimately becoming more brown. These factors alter the penetration of light into the water

because an increase in floating particles leads to a decrease in the amount of light able to penetrate the water. Instead of allowing light to penetrate the water straight through, increased particles obstruct light penetration, bouncing light rays in different directions. As the light is not able to penetrate as deep with an increased number of floating particles, the depth at which color is visible also changes (Dickey et al., 2011).

It is clear that color perception in the ocean is influenced by light penetration. There are also other factors that affect it, which makes studying color perception in the ocean very interesting. As you travel deeper in water, the range of colors that are visible are limited. Red light, which has a wavelength of approximately 650 nm is not able to travel as deep as blue light which has a wavelength of approximately 450 nm (*Exploring our Fluid Earth*).

Figure 3

Depth of Penetration of Color in Water



Note. Depiction of approximate depths at which different wavelengths of light penetrate water before they are no longer visible. Colors on opposing ends of the visible spectrum (e.g., red, orange, and violet) are fully absorbed at much shallower depths than colors in the middle range (e.g., green and blue).

Figure 1 depicts approximately how deep each color can travel underwater. These depths can be summarized in *Table 2* below:

Table 2

Colors and Their Corresponding Depth of Penetration in water

Color	Depth of Penetration (m)
Violet	43.75
Blue	112.5
Cyan	200
Green	125
Yellow	62.5
Orange	34.375
Red	18.75

Note. Average depth of penetration for each of their respective colors. This is a summary of *Figure 1* above.

Table 2 summarizes the average depth at which different colors of light penetrate ocean water. Cyan (a particular blue-green shade) light penetrates the deepest, reaching approximately

200 meters, followed by green (125 m), blue (112.5 m), yellow (62.5 m), violet (43.75 m), orange (34.375 m), and red (18.75 m). These values highlight the relationship between wavelength and light penetration and serve as a summary of the trends illustrated in Figure 1.

Cyan, which has a wavelength of approximately 492.5 nanometers (nm), penetrates the deepest in water, whereas colors such as red and violet do not penetrate nearly as deep. These relationships between colors and their penetration depth can be attributed to the optical properties of water, which takes scattering and absorption into account. This further shows that depth of penetration is not solely determined by the wavelength of the colors, but also by environmental conditions, and molecular vibrations, as well (NOAA, n.d.).

Although cyan is a helpful color name when discussing how colors penetrate underwater, throughout the rest of the thesis, it will be omitted because cyan is not a color used to describe fish. Colors such as red, orange, yellow, green, blue, and violet are, which is why these are the six colors that will be focused on extensively.

Geographic location also influences light penetration in the ocean. Near the equator, for example, sunlight strikes the ocean's surface close to perpendicular, which allows greater penetration compared to more polar regions where sunlight enters the water at a more skewed angle. As you travel deeper within water, the rate at which light is absorbed increases exponentially. Studies have shown that over 50% of visible light energy is absorbed within the first 10 meters of depth in the ocean (University of Hawai‘i, n.d.). This rapid decrease in light penetration affects both the intensity and the spectrum of light waves available at deeper depths.

Understanding the behavior of light underwater is an essential part in comprehending the effects of coloration and behavior of marine organisms. Blue-colored fish, for example, are able to remain at the surface of the ocean because they are similar in color to the water and therefore

are able to camouflage themselves at most depths. red-colored fish, however, are often found at greater depths than other colored fish. While blue-colored fish do not rely on depth to be camouflaged, red-colored fish rely on extreme depths, where red light is not able to penetrate. This pattern in fish and their corresponding depths demonstrates how the depth of color penetration influences the ecological niches of marine species. (NOAA, n.d.).

Furthermore, these patterns align with oceanic depth zones. Different zones are described in marine biology literature and are referred to as the euphotic, disphotic, and aphotic zones. The euphotic zone refers to the places where sunlight reaches and extends from the surface to around 200 meters. This zone is able to support a wide variety of both animals and photosynthetic plants. The disphotic zone is known as the "twilight" zone, as it has much less sunlight than the euphotic zone, and extends down to approximately 1000 meters. The final zone is known as the aphotic, or midnight zone, as there is no sunlight able to penetrate these depths. Photosynthesis cannot occur, and the organisms that live at these depths have evolved to survive in complete darkness (NOAA, n.d.).

Visual Systems

Human Vision

While it is important to understand the physics of colors both above and below water's surface, it is equally as important to understand how our visual systems work. This is because all of the research on fish coloration in the data used for this thesis was accumulated with respect to scientists and what they observed. It is important to understand how the colors are being perceived from the perceivers point of view.

When light enters the human eye, it follows a specific path. It begins by passing through the aqueous humor, then through the pupil, then through the crystalline lens, then the vitreous humor, until it finally reaches the retina located in the back of the eye. The retina is composed of ten distinct layers, each containing nerve cells, neural connections, and membranes. The retina also contains photoreceptor cells which are more commonly known as rods and cones. These cells are responsible for detecting, absorbing, and converting light into signals for the brain. When these receptors absorb light, they initiate a chemical reaction which then triggers an electrical signal that travels through the optic nerve to the brain. It is in this final stage where visual processing begins (Agoston, 1987).

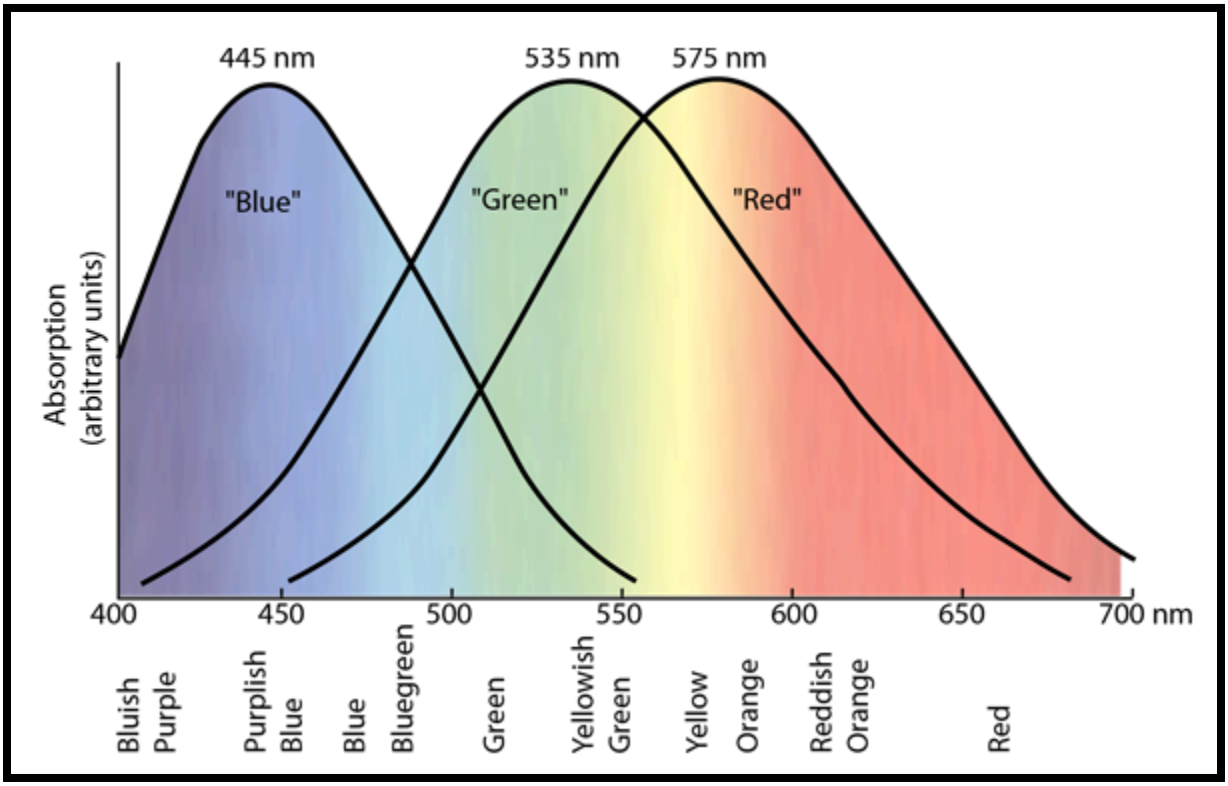
Rod cells are used in circumstances when there is little to no light. They allow humans to see in the dark, to a certain extent. In such conditions, colors can not be accurately perceived. While rods are activated in the absence of light, cone cells require more light to work. An important part of the eye is called the fovea, which is a small impression within the retina, consisting of approximately 200,000 cone cells. The fovea allows humans to see clearly and distinctly, as well as make out fine details. Cones also allow humans to discern between colors. Humans have three types of cones. Each of the three types of cones are sensitive to different types of light, including red, green, and blue light. These photoreceptors enable humans to view the full range of the visible light spectrum (Agoston, 1987).

Color perception and detection occurs in two stages. The first stage involves the red cones (L-cones), green cones (M-cones), and blue cones (S-cones). In this stage, the cones identify the amount of each wavelength present in the incoming light. During the second stage, red-green and blue-yellow channels process the information. The channels detect the presence of one of the two colors in the pair, diminishing the other. A simpler way to understand what goes

on in these channels is to think of the afterimage phenomena, where if you stare at a red object for a while then look away, a green afterimage is produced (Neitz et al., 2001).

Figure 4

Human Color-Sensitivity Curves



Note. The left-most curve, peaking at 445 nanometers(nm) corresponds to blue cones (or S-cones). The middle curve, peaking at 535 nm corresponds to green cones (or M-cones). The right-most curve, peaking at 575 nm corresponds to red cones (or L-cones). This figure was adapted from HyperPhysics, a repository created in 1998 by Associate Professor Emeritus Dr. Carl Rod Nave of the Department of Physics and Astronomy at Georgia State University, Atlanta GA. This resource contains physics content, as well as physics and astrophysics course material.

Fish Vision

While it is important to understand how the human visual system works, it is equally as important to understand how fish vision works. This is because while tracking the color of fish as they travel deeper in the water, it is crucial to understand what the fish are seeing. Surprisingly, the structure of fish eyes are similar to that of human eyes. Like humans, fish also possess a cornea, iris, lens, and retina. Unlike humans, however, their cornea tends to be more rounded. This enables fish to see up to nearly double what a human eye sees: almost 360 degrees of vision. Additionally, fish eye lenses are extremely rounded and almost spherical. This can serve as a disadvantage because in order to see an object clearly, it must be within the precise focal point. Fish are also unable to control the amount of light that enters their eyes because, unlike humans, fish are not able to increase and decrease the size of their irises. Although their eyes lack the ability to adjust their irises, they are able to compensate for this by using their retinas that can back and forth to focus in and out (What do fish see underwater, 2016).

Another similarity between fish and human eyes is that fish eyes also contain both rods and cones. This also allows them to see in low-light conditions, as well as perceive color. Many fish also have short-, medium-, and long-cones like humans. This allows them to see color within the similar visible spectrum. There are some fish species, however, that have additional cones that allow them to see ultraviolet wavelengths that extend beyond the capabilities of human color vision. Since the properties of light behave differently underwater than above water, many fish species have adapted to allow them to see in extreme depth, turbidity, and light reflection. For example, deep-sea fish tend to have more rods in order to see better in aphotic zones (What do fish see underwater, 2016).

While fish eyes and the extent to which they see are very similar to that of humans, there are many adaptations that allow them to see differently, especially in the deep sea. Since light decreases exponentially as you travel deeper into the water, it becomes dark very quickly. A human eye can theoretically detect light up to 900 meters deep, whereas some deep-sea fish are able to detect light over 1000 meters. This is due to the fact that fish eyes are much more sensitive than human eyes and are also able to detect bioluminescence in some cases (Widder, 2004).

The main takeaway is that human and fish eyes tend to have the same amount of cones– S-cones, M-cones, and L-cones– allowing them to see similar wavelengths. Although it has been studied that fish are able to detect more colors in some cases and can see at greater depths, this is important to note because as it will be shown later, fish tend to inhabit depths slightly deeper than the threshold for human color-visibility underwater.

Factors Affecting Light Penetration in Water

The Beer-Lambert Law

To understand the properties of light and color underwater, the Beer-Lambert Law can be applied. This law has proven to be a useful mathematical model that allows for the calculation of light intensity at specific depths underwater. This equation can be expressed as:

$$I_z = I_o e^{-k_{d(PAR)} * Z} \quad (3)$$

In this equation, I_z represents the light intensity at depth z, and I_o is the initial light intensity at the surface when $z = 0$, with an average value of approximately 1361 Wm^{-2} from solar radiation (Coddington et al., 2016). Additionally, $k_{d(PAR)}$ is the diffuse attenuation coefficient

for photosynthetically available radiation (PAR). It is able to measure the pace at which light diminishes as it penetrates the water. Finally, *z* refers to the depth in meters.

This exponential model is important because it not only can determine the behavior of light underwater in a controlled environment, but it can also take into account various environmental conditions. Furthermore, it can be manipulated to investigate how light penetration might change in the future, considering factors such as climate change.

Although temperature has not proven to have a direct effect on the Beer-Lambert equation, changes in temperature do affect the diffuse attenuation coefficient ($k_{d(PAR)}$). For instance, higher temperature corresponds to an increase in both salinity and the concentration of chlorophyll. Both of these factors can increase the level of turbidity in the water. With increased scattering and absorption of light due to the obstruction of light, the diffuse attenuation consequently increases. This inhibits light penetration in the water, affecting underwater environments that rely on sunlight.

These above concepts are essential for modeling the effect of time on color and light visibility. With the understanding and application of these factors, an interface can be built and utilized to predict the future visibility of light and color underwater. Such an interface can prove to be valuable when examining how marine species– especially those that live in the open ocean and rely on camouflage for survival– may adapt in response to changes in underwater visibility due to climate change.

Factors Affecting Light Penetration in Water

In order to understand how light and color penetration function underwater, it is also important to identify key factors that affect light penetration in the water. There are many

environmental factors that influence light penetration underwater. Among these factors, there are three that are extremely impactful and necessary to understand for this thesis: chlorophyll concentration, water temperature, and salinity levels.

Chlorophyll refers to the green pigment that is present in plants, algae, and phytoplankton. It plays a significant role in the absorption and reflection of light in ocean water. High concentrations of chlorophyll tend to be associated with large amounts of phytoplankton near the ocean's surface. As a consequence, the high concentration of green pigment reflects green wavelengths, while absorbing most other wavelengths (*Algae, Phytoplankton, and Chlorophyll*, 2014). As the surface is mostly reflecting green light, the ocean may appear to have a green hue. With increased organic materials at the surface, light penetration is also reduced as you travel deeper into the water. There is a significant amount of vegetation on the ocean-floor that requires sunlight to survive. A decrease in light penetration to these depths would hinder chlorophyll-rich organisms from performing photosynthesis: a necessary process that keeps them alive. A threat to the life and growth of underwater vegetation could result in negative ecological consequences.

There are many environmental effects of climate change. One of which is an increase in average ocean temperature, which is important to take note of for the importance of this thesis. Studies have shown that as water temperatures increase, there also tends to be an increase in the concentration of chlorophyll in the ocean (Hidayat, 2023). This discovery can be explained by the fact that warmer water temperatures are able to support and increase the growth of algae and phytoplankton. This in turn increases the concentration of chlorophyll in the ocean, hindering the penetration of light to deeper depths (*Turbidity, total suspended solids & water clarity*, 2019). As climate change continues to increase atmospheric and ocean temperatures, light penetration in

the ocean may continue to decrease. This can also have a unique effect on light with green wavelengths (approximately 500 nm) because with increased chlorophyll, there is also an increase in reflection of green light. Changes in light penetration underwater could significantly impact the survival of open ocean fish that rely on extreme depths to camouflage themselves. These changes in visibility may force these vulnerable species to relocate or adapt, potentially disrupting entire marine ecosystems.

In addition to its impact on marine organisms, a reduction in light penetration also threatens the survival of marine vegetation rooted on the ocean floor. If sufficient amounts of light are unable to reach these plants, they will likely die. As this factor would likely negatively affect marine ecosystems, it would also pose a negative effect on all organisms above the ocean surface, as the ocean is responsible for the production of nearly half of the world's oxygen. A decline in these plants would therefore pose a threat to humans as well. Understanding and mitigating the effects of chlorophyll on light penetration due to climate change is therefore not only a matter of marine biology, but it is also necessary for the survival of our planet.

Salinity is another equally important factor that influences the penetration of light underwater. As stated before, light enters the ocean at a plethora of different angles. These angles cause light refraction, and the extent to which it bends can be quantified by the refractive index. An increase in salinity would lead to increased light refraction because the light would be reflecting off of more salt particles. Both ocean temperature and salinity influence the refractive index. An increase in the refractive index can be attributed to an increase in salinity, whereas a decrease in the refractive index can be due to an increase in temperature (Byrne, 2024). It is evident that the refractive index and salinity have a positive correlation, while the refractive

index and temperature have an inverse relationship. These factors not only affect the direction at which light enters the water, but they also affect the depth at which light can penetrate.

The relationship between salinity and temperature is complex and can not necessarily be easily determined. A major factor that influences the relationship between salinity and temperature is geographic location. Near the equator where water temperatures are warmer, higher water temperatures tend to correspond to an increase in salinity, as higher temperatures result in an increase in evaporation, leaving more salt behind. Conversely, at locations near the Earth's poles where water temperatures are lower, increased temperatures lead to glacial melting, which in turn increases the levels of pure water, diluting the concentration of salt (Sea Water, 2023). While both scenarios seem to oppose each other, they can definitely alter the refractive index in the ocean, and by extension, the depth of light and color penetration in the ocean.

Climate Change Impacts on Light Transmission

Rising global temperatures due to climate change are significantly impacting ecosystems, with oceans and underwater marine environments being one of the most affected. As the temperatures increase, the population of phytoplankton has been rapidly increasing, causing oceans to appear greener (Chu, 2023). This observation was corroborated by recent studies indicating that climate change is affecting the perceived color of the ocean (*NASA Earth Observatory*, 2023).

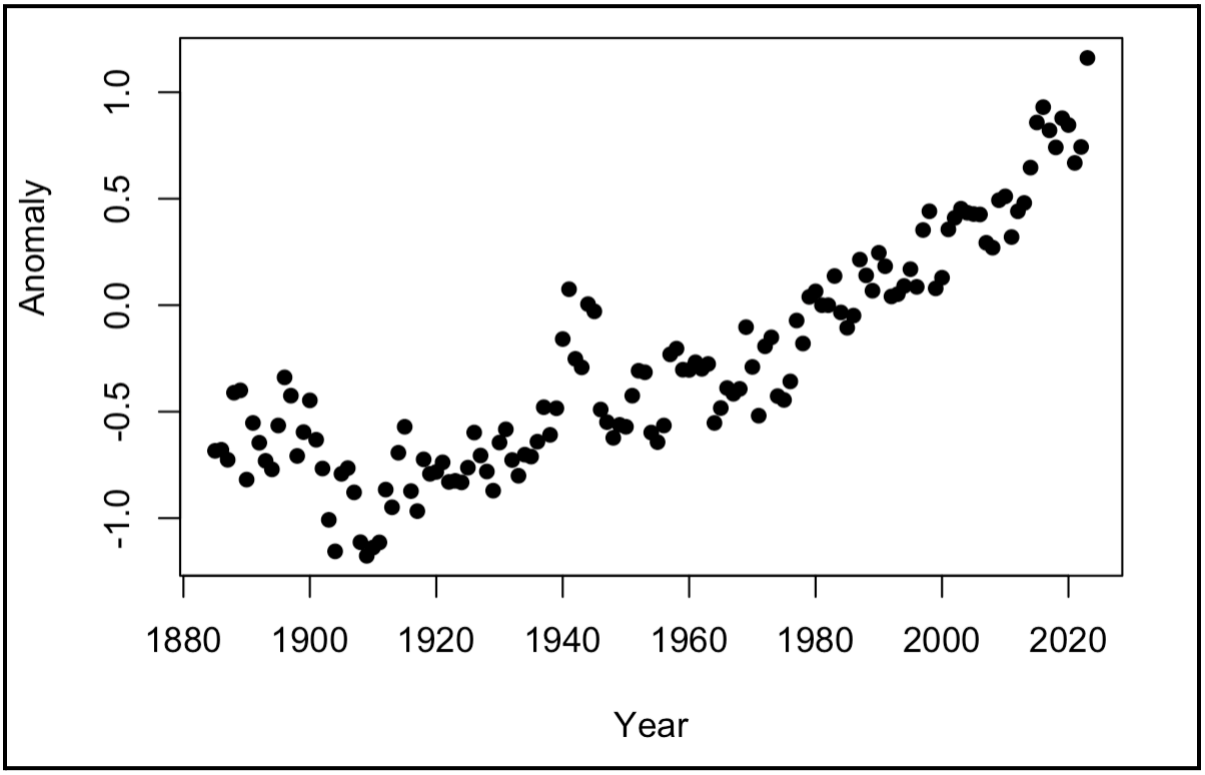
The shift in ocean color forces us to ask questions about how the wavelengths of light will travel through water. It has been proven that blue light penetrates the deepest into the ocean, which is why many fish exhibit blue coloration. It is this factor that allows them to appear camouflaged within their surroundings. However, as the ocean becomes greener in color, it may

be worth investigating whether green wavelengths will begin to penetrate deeper than blue wavelengths. If green light penetrates the deepest in the ocean, it would enable green-colored marine organisms to be better camouflaged in the open ocean and at shallower depths, while blue organisms will lose this advantage that they once had. It may be the case that fish behavior and depth location may shift, altering entire marine ecosystems.

Confirming the concern of an increase in water temperature due to global warming, the National Oceanic and Atmospheric Administration (NOAA) provided sea surface temperature data that displays a positive trend in temperature anomalies over time (Huang et al., 2017). Anomalies are used to quantify the deviation from long-term average temperatures. They are necessary for understanding climate-related changes. Due to the fact that an increase in water temperature is associated with an increase in phytoplankton and chlorophyll amounts, the data provided helps explain how the ocean may gradually become greener in hue.

Figure 5

Annual Sea Surface Temperature Anomalies



Note. Data sourced from the National Centers for Environmental Information (NCEI), and NOAA, maintained by Huang et al. (2017). This dataset supports long-term global and basin-specific sea surface temperature studies in degrees Celsius. It provides a visual representation of annual sea surface temperature anomalies from 1854 to present, and shows how the anomalies display an upward trend. The positive correlation between time and anomaly reflects an increase in average ocean temperatures over time.

While the green appearance of the oceans has been documented over time, its direct effect on marine life remains insufficiently studied. The increase in light absorption and scattering due to increased chlorophyll levels could significantly impact not only the visibility

and location of fish beneath the surface of the ocean, but also predator-prey dynamics. Future research is necessary to further explore how such changes may affect marine ecosystems over time.

Previous Studies on Fish Camouflage

Operation Deep Scope

In 2004, a team of thirteen scientists—including Don Colling, Tamara Frank, Erika Heine, Sönke Johnsen, Brian Johnson, Justin Marshall, Mikhail V. Matz, Charles H. Mazel, Nicole McMullen, Mark Schrope, Alison Sweeney, Edith A. Widder, and Jörg Wiedenmann—embarked on a scientific expedition into the Gulf of Mexico, known as Operation Deep Scope. Their primary objective was to observe, categorize, and count marine life in the deep sea with minimal disturbance to both the marine environment and the organisms. The team chose the Gulf of Mexico as their location due to its ecological diversity and increasing exposure to oil and gas pollution. While in the Gulf, they chose four distinct sites to carry out their research: the western edge of the DeSoto Canyon, Lophelia coral formations of Viosca Knoll (a deep-water reef), areas near methane seeps with a large population of clams and worms that feed on methane-eating bacteria, and the Brine Pool, where denser, saltier water creates a unique microhabitat.

Traditional methods used to study fish anatomy and environment not only disturbed surrounding habitats, but they also harmed marine life and frequently concluded with inaccurate data. In order to combat these issues, the Deep-Scope team designed a contemporary device they referred to as the *Eye-in-the-Sea*.

The *Eye-in-the-Sea* was a self-contained, battery-powered, low-light-level camera that contained red LEDs. This combination allowed the camera to detect and capture deep-sea organisms. The *Eye-in-the-Sea* was constructed with specific requirements to ensure the safety of both the organisms and their environment. The wavelengths chosen in capturing data and images of the organisms are invisible to most deep-sea species, which allowed the scientists to observe the organisms' behaviors and characteristics without disturbing them. When the team began collecting data, they deployed the *Eye-in-the-Sea* at specific locations for 24-hour periods at a time. At each location, the device was deployed two times, once using bait to attract marine organisms, and another without any incentives to capture the organisms' natural behaviors.

In addition to the *Eye-in-the-Sea*, the team of scientists constructed a light-tight trap, specifically designed to temporarily confine organisms in a manner that would not cause them any harm. This trap allowed the scientists to collect important information about the marine organisms, such as their visual pigments, optical structures, and the overall sensitivity of their eyes. The ultimate goal of this project was to better understand the visual systems of marine organisms, especially those at extreme depths, where sunlight does not reach.

With the use of a highly sensitive spectrometer, the researchers also measured the intensity and wavelength of sunlight present at each of the data collection sites. This information is an essential part in understanding how light behaves at different depths within the ocean, as well as how light, or lack thereof, influences organism visibility and camouflage.

After the completion of their research, the team discovered that there was a consistent pattern between the coloration of marine organisms and the depths at which they lived. They were able to come to three important conclusions. First, they noticed that organisms living closer to the surface tend to have more of a blue coloration, a characteristic that might help them blend

in with the surrounding water and light. They also saw that organisms living in midwater zones typically had undersides that were less saturated in color than their backs. This would likely help them camouflage in the water from above and below. Finally, the scientists discovered that organisms living at the deepest depths were typically transparent, red, black, or pink. Organisms of these colors rely on extreme depths to appear camouflaged within their surroundings (Johnsen, 2004).

In order to quantify the relationship between the amount of natural light in a region and the coloration of organisms, the researchers used advanced instrumentation. One such machinery that was used to test this relationship was the Johnson-Sea-Link submersible which was able to measure the amount of absorbed and scattered light at varying volumes of seawater. Another piece of equipment consisting of spectrometers and xenon light sources was used to capture accurate color data from the animals themselves. This instrument was able to do so by emitting both visible and ultraviolet wavelengths, which was then transmitted through a fiber-optic cable which ultimately illuminated the organism. The reflected light was collected and analyzed by the spectrometer to determine the exact hue and saturation across a range of wavelengths.

Although the methods employed in Operation Deep Scope produced high-quality data on marine camouflage and visibility, the sample size was extremely limited. A more comprehensive dataset would be required to draw broad conclusions applicable to global marine ecosystems. The adaptation of similar methods on a larger scale, of both location and organisms tested, could potentially offer an invaluable resource for understanding how marine animals use color and camouflage to survive.

Distribution Mapping and Analysis Portal

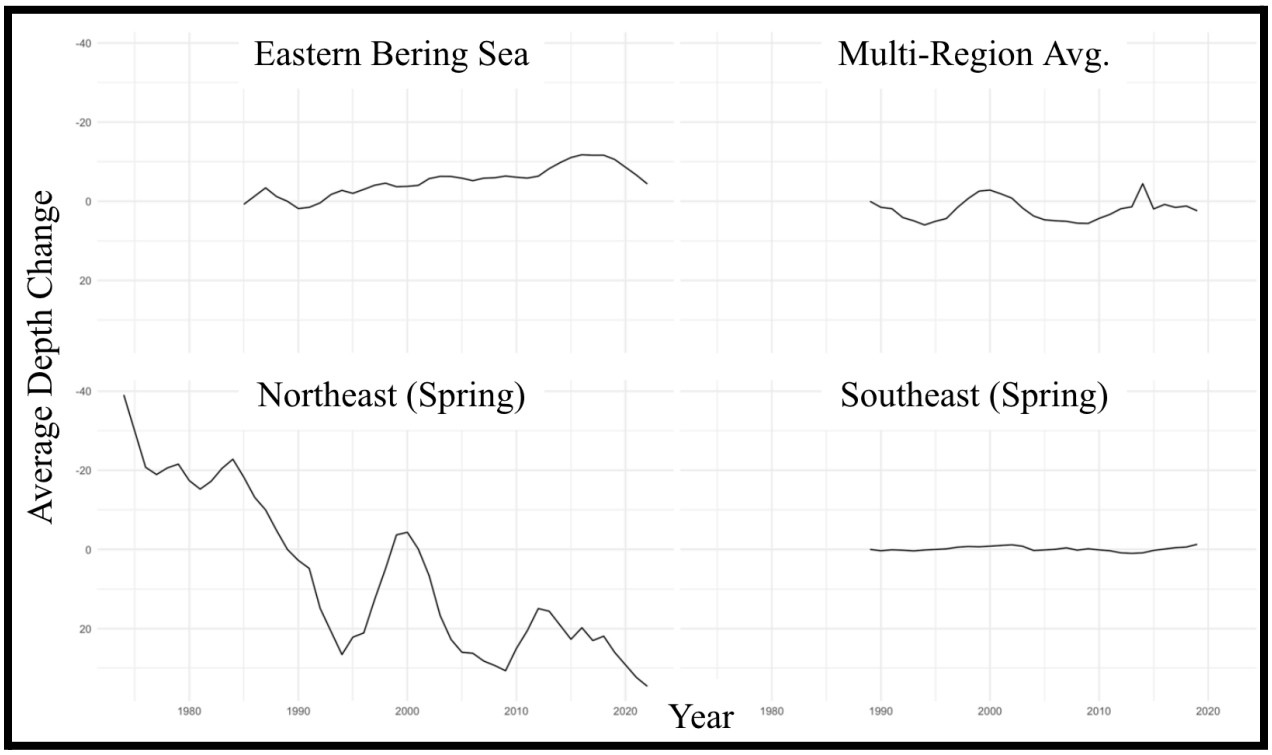
In order to fully understand the increasing effects of climate change over the years, the National Oceanic Atmospheric Administration (NOAA) has been conducting incredible amounts of research to monitor and understand marine ecosystems. Their findings not only corroborate previous studies and research, but it also has proven to be beneficial for fishers, policy-makers, and environmental agencies, all of whom rely on the protection and well-being of marine life.

Although fish migration and geographic distribution have been widely studied, depth tracking with respect to time has received little attention. The NOAA, however, have gathered data on approximately 400 marine species, documenting their depth and latitude changes across different seasons and regions. Their findings were made public and published in an interactive platform known as the *Distribution Mapping and Analysis Portal (DISMAP)*. DisMap offers users access to spatial data on species distributions across a wide range of locations. The main goal of this project was to provide insight and accessibility on species distribution data to a wide variety of users (Haverland, 2022).

The unique aspect of this NOAA dataset is its long-term tracking of specific species from approximately 1989 to the present. Although it does not focus on species coloration, it does provide valuable depth trends over time for numerous marine organisms. Their findings provide clear observations of longitudinal shifts in where fish tend to frequent, which may be a result of climate change and environmental changes. Methods that were used to collect this data can be implemented in the future to hopefully make a larger scale dataset.

Figure 6

Average Fish Depth Change over Time in Four NOAA Regions: Eastern Bering Sea, Multi-Region Average, Northeast (Spring), and Southeast (Spring).



Note. Data exported from the NOAA and analyzed in R to visualize the average fish depths by region over time. The y-axis is inverted for clarity, showing deeper depths lower on the graph. Trend lines represent the slope of average depth change per year. Statistically significant changes are indicated by p-values less than 0.05. Data created by Timothy J Haverland from NOAA's Distribution Mapping and Analysis Portal (DisMap) (Haverland, 2022).

While the above trends are visually intuitive, statistical analysis was also performed to quantify the changes and determine significance through regression slopes and p-values.

Table 3

Summary of Average Fish Depth Trends in Four NOAA-Defined Regions

Region	Slope	P-Value
Eastern Bering Sea	-0.286	4.10e-12
Multi-Region Average	-0.0204	7.19e-1
Northeast (Spring)	1.23	1.30e-16
Southeast (Spring)	0.00105	9.30e-1

Note. This table summarizes linear trend estimates of average fish depth over time in four NOAA-defined regions. Slope values represent the average change in fish depth (in feet) per year. Negative slopes indicate shallower movement, while positive slopes suggest fish are moving deeper over time. P-values less than 0.05 (e.g., Eastern Bering Sea and Northeast (Spring)) indicate statistically significant trends. Data sourced from NOAA's Distribution Mapping and Analysis Portal (DisMap) and analyzed in R.

Figure 6 presents graphical representations of average fish depth trends in four NOAA-defined regions over time, while Table 3 summarizes the results from the graphs. In the Eastern Bering Sea, the regression slope is -0.0286, and the associated p-value is 4.10e-12. Since this value is below $\alpha = 0.05$, the trend is statistically significant. It can be stated that on average, fish in this region appear to migrate approximately 0.0286 feel shallower per year. The multi-region average, however, shows a slope of -0.0204 with a p-value of 0.719, indicating no significant depth change over time. In contrast, the Northeast (Spring) region displays a positive slope of 1.23 with a highly significant p-value of 1.30e-16, suggesting fish in this area are

moving deeper by about 1.23 feet per year. The Southeast (Spring_ region has a slope of 0.00105 and a p-value of 0.9301, showing no statistically significant trend.

Although NOAA's research does not focus on fish coloration, it supports the broader concept of fish depth variability over time. Their work suggests that climate change may influence longitudinal migration, with fish seeking deeper, cooler waters as surface temperatures rise. While the reasoning in this thesis is more closely linked to camouflage and visibility, these NOAA findings complement the overall hypothesis: that fish may adapt their depth as a response to changing environmental conditions.

Methods

Data Sources and Collection

FishBase

The primary source of data used in this thesis is derived from *FishBase*. *FishBase* is a comprehensive online database that compiles extensive information about fish species from around the world. As of the most recent update, published on January 12, 2025, *FishBase* includes contributions from experts such as Carl Boettiger, Scott Chamberlain, Duncan Temple Lang, Peter Wainwright, Kevin Cazelles, and Guohuan Su. The database is currently being maintained by Carl Boettiger. *FishBase* is home to a plethora of data, containing approximately 35,800 species, 65,100 images, 63,000 references, all contributed from over 25,00 collaborators.

FishBase provides a significant amount of information for each species, including scientific classification, common names, habitat regions, biological descriptions, life cycles, and more. The credibility of *FishBase* relies on the information submitted and curated by professionals and researchers in the field. They ensure the reliability and validity of the information contained in the database. *FishBase* served as the foundation for the data analyzed throughout this thesis.

rfishbase

All of the data analysis and manipulation for this thesis was conducted using the programming language R. For those interested in learning more about coding in R, there are numerous online tutorials and documentation that can assist beginners as well as advanced users. A majority of this thesis involved creating, organizing, and analyzing data, primarily using the R

package *rfishbase*. *rfishbase* serves as an interface to *FishBase*, enabling seamless access to its extensive repository of fish data.

rfishbase allows its users to retrieve specific tables and species data directly into R, proving it to be an invaluable tool for researchers conducting large-scale biological or ecological analyses. While *rfishbase* allows access to *FishBase* and all the data included, it also allows users to access the data to its sister database: *SeaLifeBase*. *SeaLifeBase* contains information on over 200,000 species of non-fish aquatic life such as marine mammals and reptiles. Although this thesis only required data from *FishBase*, it is worth noting that there are many other aspects to *rfishbase* that allow a wide variety of people to conduct research.

My full R code can be accessed on github with the following url: https://github.com/kapoulathas/PoulathasThesis.git

Working with the Data

Useful Functions

A key advantage of using *rfishbase* is that it has a user-friendly structure that organizes data into comprehensive tables that can be easily filtered and visualized. *rfishbase* works in tandem with the *FishBase* Application Programming Interface (API) to ensure that the data available in the package is accurate and up-to-date. Within *rfishbase*, there are approximately 47 distinct functions that allow for the retrieval and manipulation of available data.

Within *rfishbase*, there are three functions, in particular, that were proved to be essential in the data collection process. These useful functions included `fb_tbl()`, The `fb_tables()`, and `species()`. The `fb_tbl()` function allows users to access specific tables from either *FishBase* or *SeaLifeBase*. The `fb_tables()` function returns a list of all available tables within the specified database, containing useful overviews of information within relevant datasets.

Finally, the `species()` function retrieves a number of specific information for a given fish species. These functions, combined with R's useful data handling capabilities, made data analysis possible for this research.

After installing appropriate packages, *rfishbase* users can see the 634 available tables by running the following function commands:

```
> fb_tables()
```

```
[1] “”                  “abnorm”          “abnormref”       “abundance”
[5] “abundancedelta”    “aknowledge”      “address”         “airbreathingref”
[9] “alieninvasive”     “allgenus”        “aquamaint”       “aquamaps”
...
```

Within these tables, there are an abundance of available variables that can be accessed. The variables I focused on were accessed from the 'species' table in 'FishBase'. While using the following code, users must make sure to specify first, which table they want to select, and second, from what interface (ex: 'FishBase' or 'SeaLifeBase').

```
> fb_tbl("species", "fishbase"))
```

SpecCode	Genus	Species	SpeciesRefNo	Author	FBname
<int>	<chr>	<chr>	<int>	<chr>	<chr>
64588	Aaptich…	webste…	78622	Hube…	NA
16239	Aaptosyax	grypus	10431	Rainb…	Giant…
2347	Abactochromis	labros…	85491	Trew…	NA

```
...
```

The above function provides a table with 102 variables for each of the fish in the dataset. Here, `fb_tbl()` is the function, while “species” is a character string that specifies which table we want to look at. Conversely, if the `species()` function is run:

```
> species()
```

SpecCode	Genus	SpeciesRefNo	Author	FBname
<int>	<chr>	<int>	<chr>	<chr>
64588	Aapticheilichthys	78622	Huber	NA
16239	Aaptosyax	10431	Rainboth	Giant...
2347	Abactochromis	85491	Trewavas...	NA
...				

Variables

rfishbase has a wide variety of variables. As stated before, there are 102 available variables in the species table, alone. Such variables are presented as the columns in the tables. The variables of interest for this thesis include “Genus”, “Species”, "FBname", “DepthRangeShallow”, “DepthRangeDeep”, and “DemersPelag”. More detail on the variables and their uses will be explained in more detail in the following section.

Usage

The *rfishbase* package provides users with easy access to information contained in *FishBase*. As it is one of the largest and most comprehensive global databases of fish species, *FishBase* is widely used by a range of people, including scientists, fisheries, educators, students, conservationists, and climate professionals (Boettiger et al., 2012). The database offers both general and highly detailed information on 35,800 fish species, making it valuable to not only advanced researchers, but also amateur users.

One of the primary advantages of using *rfishbase* is that it allows its users to access an extensive collection of regularly updated data from *FishBase* that was curated by professionals. Its organization and user-friendly structure allows for easy access and usage for beginners, while its wide array of functions used for sophisticated data manipulation and visualization can be used by more experienced users.

Despite its countless advantages, *FishBase* has a few limitations that are worth noting. First, the quality and completeness of the data depend heavily on contributions from researchers and institutions, which may lead to inconsistencies in data coverage and reliability. Additionally, well-studied or commercially important species tend to include more data available than lesser-known species. This factor creates unwanted gaps in data. Finally, the online nature of the database makes it vulnerable to technical issues, including slow performance during periods of high usage.

Data Crunching, Munging, and Manipulation

After becoming familiar with the *rfishbase* package and its nuances, a necessary next step is to begin the process of extracting and organizing the data necessary to answer important

questions. In order to quantify and visualize the possible relationship between fish color and depth, information of fish species including their depth ranges, habitat zones, and colors are necessary. While specific fish coloration data is not readily available for extraction in *FishBase*, detailed information about species' location and depth are accessible. Therefore, the "species" table was extensively accessed from *FishBase*, and stored in a variable named `fish_data` for easy identification. Although the table included a large number of variables, many of them were not relevant to the research in this thesis.

```
> fish_data <- fb_tbl("species", "fishbase")
> fish_data
```

SpecCode	Genus	Species	SpeciesRefNo	Author	FBname
<int>	<chr>	<chr>	<int>	<chr>	<chr>
64588	Aaptich…	webste…	78622	Hube…	NA
16239	Aaptosyax	grypus	10431	Rainb…	Giant…
2347	Abactochromis	labros…	85491	Trew…	NA
...					

The resulting data frame contains thousands of fish species entries with attributes such as genus, species name, reference numbers, authorship, adn common name. While the available information is useful, many columns and rows were deemed irrelevant or incomplete. To streamline the date, specific functions can be used to extract relevant columns such as "Genus", "Species", "FBname" (common name), "DepthRangeShallow", "DepthRangeDeep", and "DemersPelag". These selected columns were stored in a variable named "my_fishies", which

used the `na.omit()` function to remove any rows with missing values, creating a cleaner dataset named `new_species_depth_filtered`.

```
> my_fishies <- fish_data[c("Genus", "Species", "FBname",
                            DepthRangeShallow", "DepthRangeDeep",
                            "DemersPelag")]
> new_species_depth_filtered <- na.omit(my_fishies)
> write_xlsx(new_species_depth_filtered, "mySpeciesExcel2.xlsx")
```

```
> new_species_depth_filtered
```

Genus	Species	FBname	DepthRange Shallow	DepthRange Deep	DemersPelag
<chr>	<chr>	<chr>	<int>	<int>	<chr>
Abalistes	stellatus	Starry triggerfish	7	350	reef-associated
Abantennarius	analis	Tailjet frogfish	2	21	reef-associated
Abantennarius	bermudensis	Island frogfish	4	30	reef-associated
Abantennarius	coccineus	Scarlet frogfish	10	75	reef-associated
Abantennarius	dorehensis	New Guinean frogfish	0	10	reef-associated
...					

Each column serves a specific purpose: "Genus" and "Species" provided the taxonomic classification for each specified fish, "FBname" provided the common name, and the "DepthRangeShallow" and "DepthRangeDeep" columns depicted the depth ranges in meters in which each of the species are typically found. Finally, the "DemersPelag" column provides classification for each fish species into one of the nine habitat categories: benthopelagic, pelagic,

demersal, pelagic-neritic, reef-associated, bathypelagic, bathydemersal, pelagic-oceanic, or unknown. These categories are crucial for analyzing the potential relationship between fish and their depths.

The complete dataset of fish used in this thesis was filtered down to 9,806 rows. Each of which represents a unique fish species with its associated complete and relevant data. Further processing of the data was carried out in Excel after exporting it. In Excel, a new column was added, labeled “Color”, where the dominant hue of each fish was manually inputted into each row. Unfortunately, comprehensive color data, including wavelength-specific spectra, is not available in the *FishBase* interface. As a result, extensive research was performed on each species using descriptions and images provided by *FishBase* in order to determine the most dominant color for each fish.

To standardize this manual process, a categorical color scheme was developed with seven options: red, orange, yellow, green, blue, violet, and other. Because most fish cannot be characterized by one single color, the most visually dominant hue for each fish was selected, based on descriptions and photographs. A common example of a color description for many fish was “silvery coloration”. In instances such as these, they were labeled as “other”. There were also a significant amount of fish that could be characterized as “pink”. Instead of creating a new characteristic color, pink fish were grouped under “red” since pink ultimately shares the same hue as red. While characterizing fish color based off of their pictures, it was critical that the color recorded reflected the appearance and coloration of the live fish. It was crucial to understand that many images can not be trusted as they are taken post-mortem. In such cases, fish often change color after their death due to a drop in oxygen levels, as well as appearing more yellow in color due to chemical preservatives.

Although the color classification process posed a tedious task, it was necessary for the integrity of the dataset. Once complete, the fish data, as well as their corresponding colors, were saved as a .csv file to facilitate further analysis in R. CSV files are important when manipulating data in R because they allow for easy reading and editing of data. After opening the complete data in R, graphs and statistical analyses could be conducted.

```
> df.newNewSpeciesDepth = read.csv(file = 'Desktop/thesis/mySpeciesExcel2.csv')
```

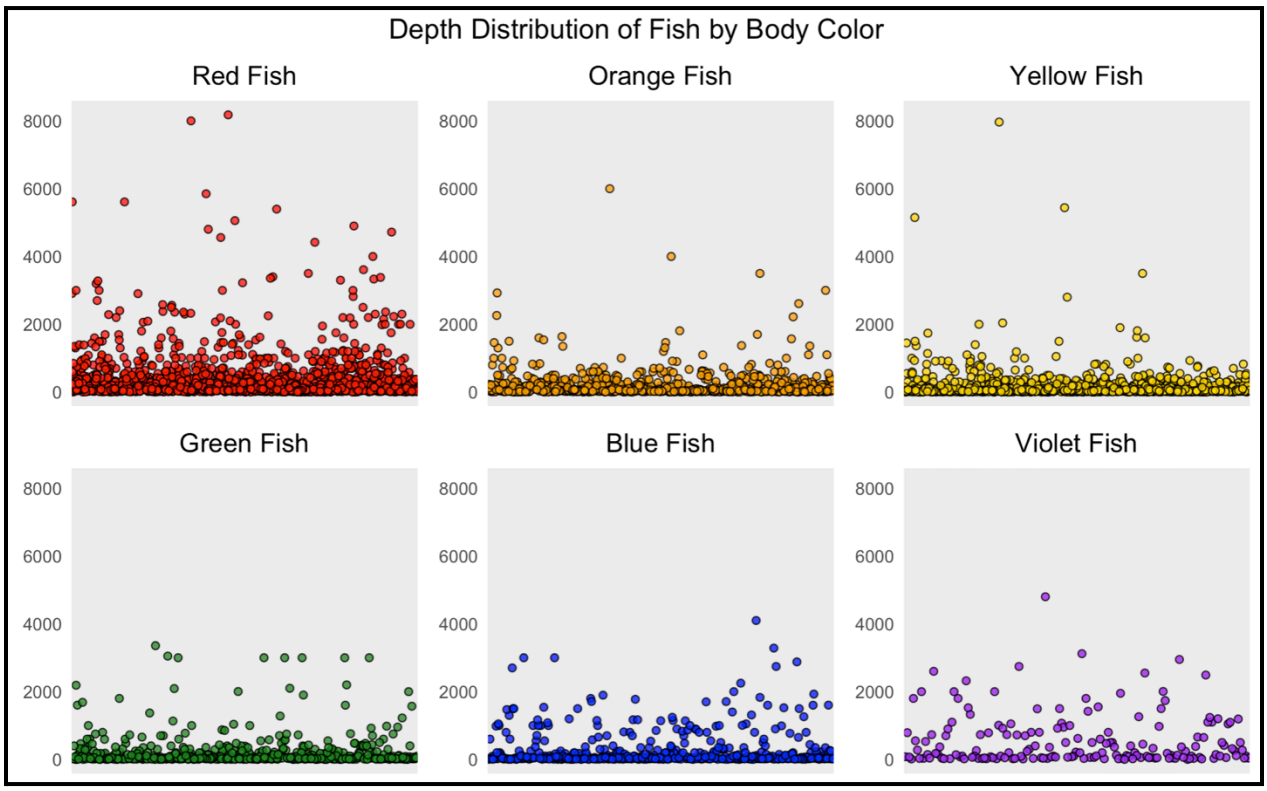
The next phase involved graphing the data to visualize a possible relationship between fish coloration and their corresponding depth ranges. New data frames were created– each filtered by a specific color– using the naming convention "df_filteredCOLOR" (e.g., df_filteredRED, df_filteredBLUE). With the use of the ggplot2 package, visualization of depth distribution of each color category was easily generated. Summary statistics were also calculated for each group, including the count, mean, median, and minimum and maximum depths. The visual representations coupled with numerical interpretations aided in the process of identifying patterns and correlations between fish coloration and depth. Furthermore, the outputs provided critical insight into how visibility and habitat zones may affect evolutionary behaviors of marine species.

Data Visualization

Produced graphs can be seen below. Only fish of colors including red, orange, yellow, green, blue, and violet were graphed. This is because these are the hues included in most wavelength penetration data. Colors such as white, black, gray, and brown are seldom included in wavelength penetration graphs, and were therefore excluded from these graphs.

Figure 7

Depth Distribution of Fish by Body Color



Note. Each of the above scatter plots represents the depths at which each fish resides, across their body colors: red, orange, yellow, green, blue, and violet. The y-axis represents the depth, in meters. The data were retrieved using information available in *FishBase* and the *rfishbase* package.

Table 3

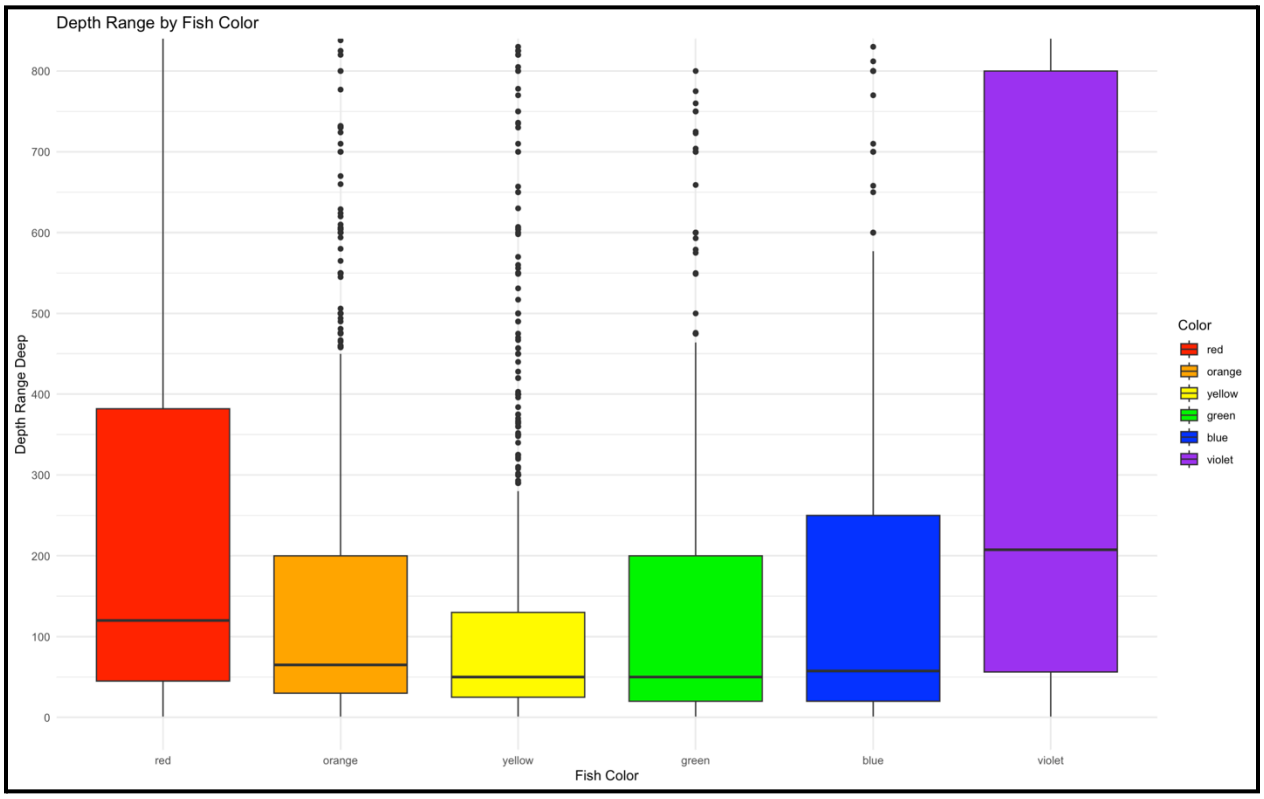
Summary Statistics of Depths of Fish of Different Colors

Color	Count	Mean Depth	Median Depth	Min Depth	Max Depth
Red	1441	417.8008	160	1	8178
Orange	810	202.3593	65	1	6000
Yellow	1883	158.0507	50	1	7965
Green	535	225.8262	50	1	3356
Blue	450	304.3882	57.5	1	4099
Violet	170	574.4529	207.5	1	4800

Note. The above table displays descriptive statistics for fish of different colors, including sample size (Count), average depth (Mean), and depth range (Min, Max). Depth values are measured in meters. These statistics were calculated using data obtained from the *FishBase* database via the *rfishbase* package.

Figure 8

Depth Range by Fish Color



Note. Data above depicted in the scatterplots are here represented in the form of boxplots so that the differences in depth can be easily visualized and compared. The boxplots represent the depths at which each fish resides, across body colors of red, orange, yellow, green, blue, and violet. The y-axis represents the depth, in meters. The data were retrieved using information available in *FishBase* and the *rfishbase* package.

To evaluate whether or not there were statistically significant differences in the depth ranges at which fish of different colors are found, a Kruskal-Wallis rank wun test was conducted.

This non-parametric test was appropriate to use due to the non-normal distribution of depth data across color categories.

Table 4

Kruskal Wallis Test for Depth Range by Fish Color

Kruskal-Wallis rank sum test
Data: DepthRangeDeep by Color
Kruskal-Wallis chi-squared = 240.26, df = 5, p-value < 2.2e-16

Note. The Kruskal-Wallis test was used to determine whether there are statistically significant differences in depth ranges among fish of different colors. The result indicates a significant difference across groups (chi-squared = 240.26, p-value < 2.2e-16).

The null hypothesis stated that there would be no difference in the typical depth ranges across fish colors, simply meaning that all colors of fish tend to be located at similar depths on average. The Kruskal-Wallis test result concluded a highly significant p-value (less than 0.001), which was significantly less than $\alpha = 0.05$. Therefore, the null hypothesis was rejected, indicating that depth ranges vary significantly by fish color.

The median depth values for each color revealed an interesting trend. Red and violet-colored fish displayed deepest depths overall, with median depths of 160 and 207.5 meters, respectively. In contrast, orange-colored fish had a median depth of 65 meters, yellow and green both had median depths of 50 meters, and blue-colored fish had a median depth of 57.5 meters. This suggests that fish displaying colors from the far ends of the visible light spectrum (i.e. red and violet) tend to correspond to deeper waters than fish with colors corresponding to wavelengths in the middle of the spectrum (i.e. orange, yellow, and green).

This pattern is consistent with how light travels through water. Wavelengths at the red and violet ends of the visible light spectrum are absorbed more quickly and do not penetrate as deeply into the ocean. As a result, fish with red coloration can be completely camouflaged into their surrounding environment. Although red light is absorbed at much shallower depths, red fish rely on extreme depth the most in order to be entirely camouflaged within their environment. Although blue light penetrates the deepest, fish with blue coloration do not rely on extreme depths for concealment because they are able to camouflage into the surrounding water at any depth.

Although there is a trend between fish coloration and their depth, there are also a significant amount of red and violet fish that live in shallow waters. Fish such as these are commonly found in shallow coral reef environments. As they can not depend on extreme depths for camouflage, their strategy for avoiding predation often involves hiding within coral structures or beneath rocks. In open-water environments where physical shelter is limited or absent, camouflage becomes critical for survival. Fish that rely on depth-related camouflage in such settings use depth for concealment. Red fish, for instance, would be highly visible in shallow waters, forcing them to reside in deeper waters for concealment. Blue fish, however, are able to remain less detectable at most depths due to the fact that they are able to blend into the blue background of the surrounding water.

The findings relating color to depth support the idea that coloration in marine species is not random, but instead plays an important role in organism survival.

Condensed Data Visualization

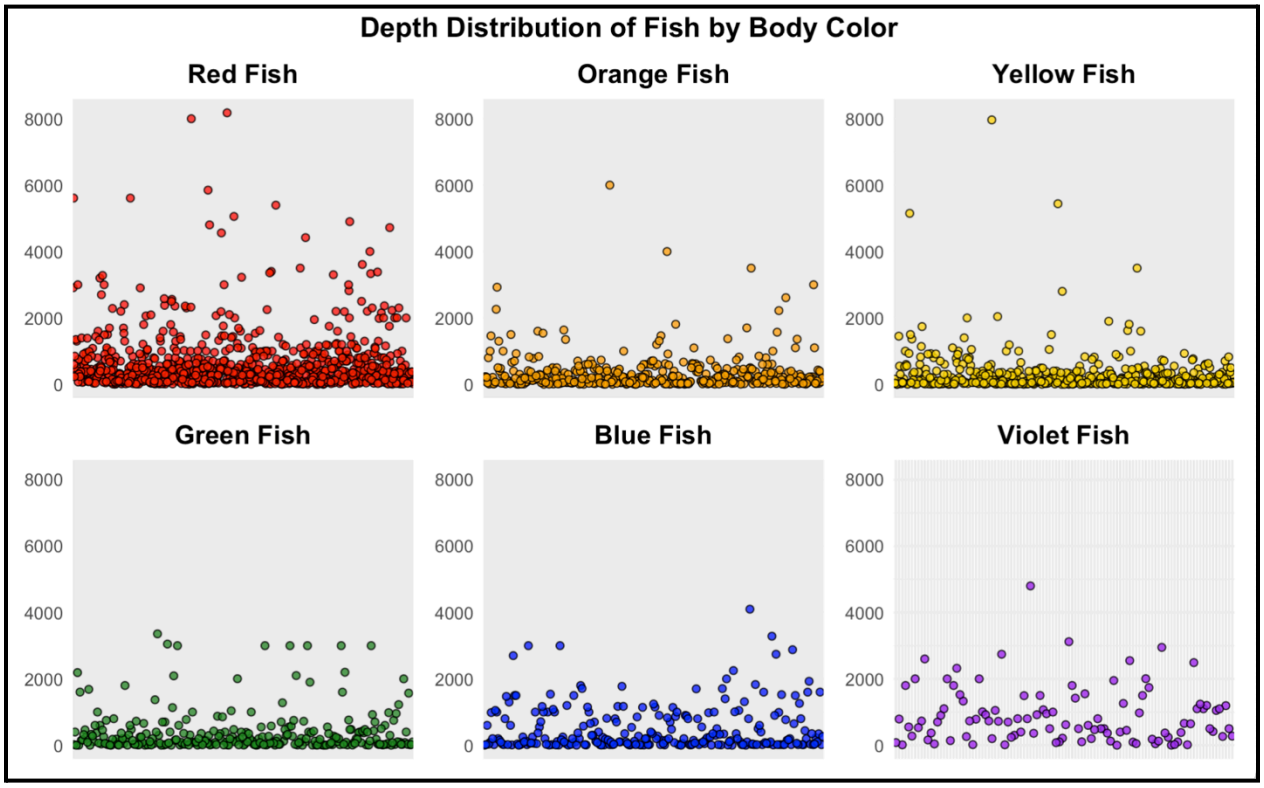
The relationship between the color of fish and their depth can be further tested if a filter is applied to the data. Instead of including all 9,806 fish, it is important to study the relationship between fish color and depth, only for fish that live in the open water. In other words, fish that reside in coral reefs will be excluded because they do not rely on camouflaging into their surroundings like open-water fish do.

With the use of the "dplyr" function, the data was able to be further filtered. As it was important to study depth of fish that were considered to be "open-water" fish, the removal of "reef" fish is necessary. After the completion of this removal, the new data was saved into a data frame called "df.onlyYnewSpeciesDepth". Saving altered data into a new data frame each time alterations occur is crucial, as it allows for easy manipulation and correcting if mistakes are made.

The visualization of this new filtered data is available in the below tables and figures:

Figure 9

Depth Distribution of Fish by Body Color for Open Ocean Fish



Note. Each scatter plot represents the depth at which each fish resides, across body colors of red, orange, yellow, green, blue, and violet. The data is filtered so that only fish that reside in the open ocean are included. The y-axis represents the depth, in meters. The data were retrieved using information available in *FishBase* and the *rfishbase* package.

Table 5

Summary Statistics of Depths of Fish of Different Colors for Open Ocean Fish

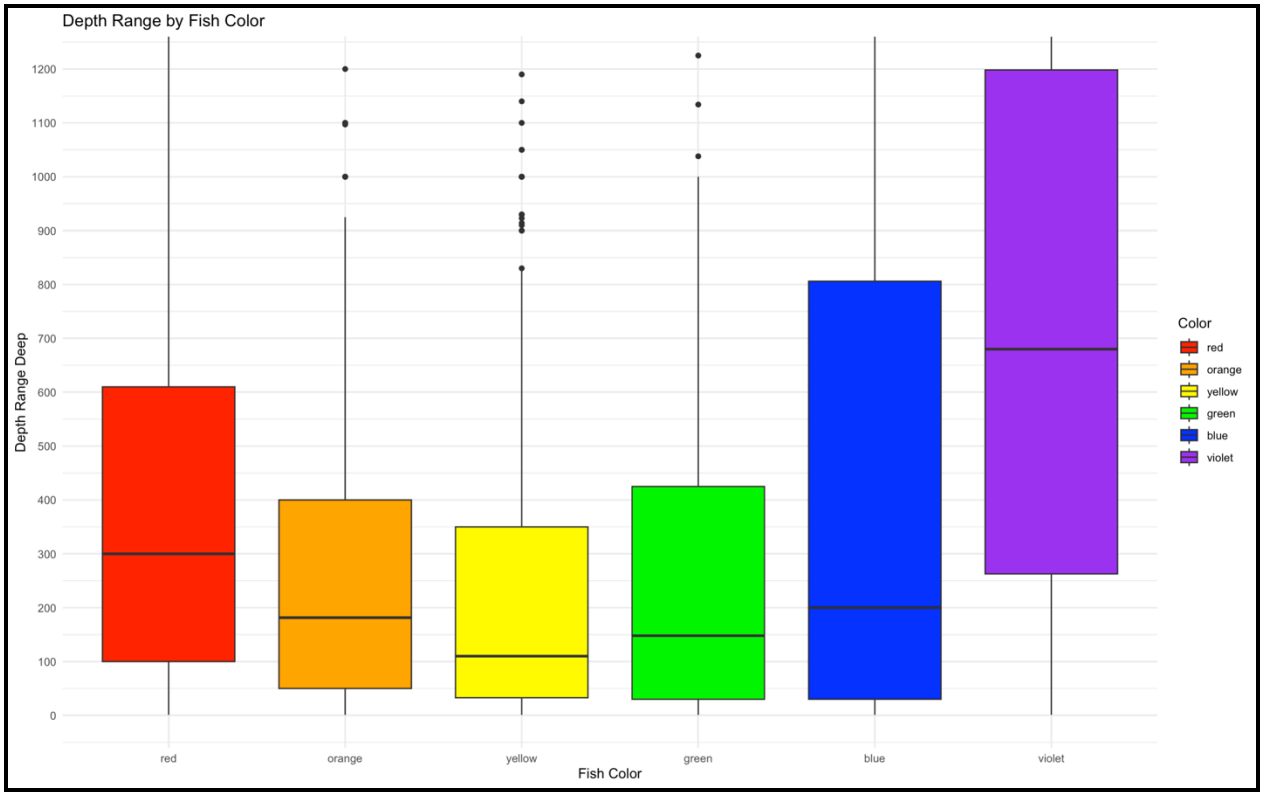
Color	Count	Mean Depth	Median Depth	Min Depth	Max Depth
Red	893	616.7828	350	1	8178
Orange	392	343.801	181.5	1	6000

Yellow	468	298.3718	110	1	7965
Green	272	393.3382	158	1	3356
Blue	247	502.6073	200	1	4099
Violet	106	877.2547	680	1	4800

Note. This table displays descriptive statistics for open ocean fish of different colors, including sample size (Count), average depth (Mean), and depth range (Min, Max). Depth values are measured in meters. These statistics were calculated using data obtained from the *FishBase* database via the *rfishbase* package.

Figure 10

Depth Range by Fish Color for Open Ocean Fish



Note. Data above depicted in the scatterplots are here represented in the form of boxplots so that the differences in depth can be easily visualized and compared. The boxplots represent the depths at which open ocean fish resides, across body colors of red, orange, yellow, green, blue, and violet. The y-axis represents the depth, in meters. The data were retrieved using information available in *FishBase* and the *rfishbase* package.

Table 6

Kruskal Wallis Test for Depth Range by Fish Color for Open Ocean Fish

Kruskal-Wallis rank sum test
Data: DepthRangeDeep by Color
Kruskal-Wallis chi-squared = 205.73, df = 5, p-value < 2.2e-16

Note. The Kruskal-Wallis test was used to determine whether there are statistically significant differences in depth ranges among fish of different colors. The result indicates a significant difference across groups (chi-squared = 205.73, p-value < 2.2e-16).

A Kruskal-Wallis test was conducted to evaluate whether or not there were statistically significant differences in the depth ranges among open ocean fish of different colors. This nonparametric test was selected due to the potential for non-normal distribution in the data. The analysis revealed a significant difference in depth ranges across fish colors (chi-squared = 205.73, p-value < 2.2e-16), indicating that depth range varies depending on color.

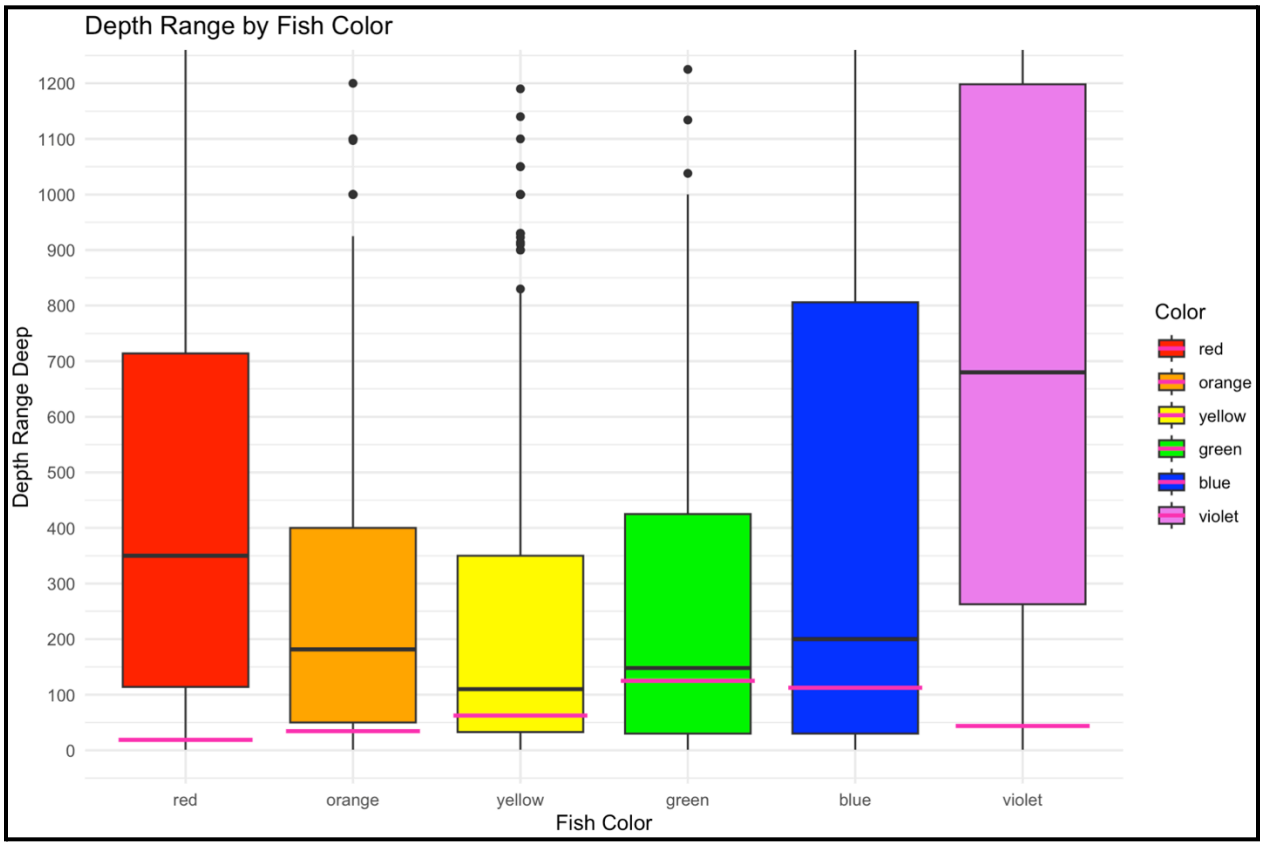
The null hypothesis stating that fish of different colors occupy the same average depth was rejected. Instead, we favor the null hypothesis, which states that fish of different colors occupy different depths. With a p-value of < 2.2e-16 which is less than 0.001, it can be stated that there is strong evidence against the null hypothesis, supporting the conclusion that color is associated with the depth range at which fish are found.

The median depth values for each color group were as follows: red = 350 meters, orange = 181.5 meters, yellow = 110 meters, green = 148 meters, blue = 200 meters, and violet = 680 meters. These results suggest a pattern where fish with colors located at the ends of the visible light spectrum (red and violet) tend to inhabit deeper water, whereas those with mid-spectrum colors(e.g., yellow, green, and blue) are found at shallower to moderate depths.

This pattern aligns with known principles of light penetration in water. Longer wavelengths such as red and shorter wavelengths like violet are absorbed quickly in shallow water, rendering fish of these colors nearly invisible at greater depths. Thus, red and violet fish may rely on deeper water to remain concealed from predators or prey. In contrast, mid-spectrum colors, particularly blue, penetrate deeper and match the color of the surrounding ocean, allowing fish of these hues to camouflage effectively without needing to occupy greater depths.

Figure 11

Depth Range by Fish Color for Open Ocean Fish with Line of Invisibility



Note. This boxplot shows the distribution of depth ranges for open ocean fish categorized by color. The bright pink horizontal lines within each box represents the approximate depth at which

that color becomes “invisible” in water, based on *Table* 2, which summarized the depths at which each color can penetrate in water before disappearing completely. The plot indicates that fish colored red and violet– colors at the extreme ends of the visible spectrum– are consistently found at or below the depth at which their coloration becomes invisible. In contrast, fish colored yellow, green, and blue display wider variation, with some individuals found above their respective invisibility thresholds.

The above findings support the hypothesis that fish with red or violet coloration rely more heavily on extreme depths as camouflage mechanisms in order to avoid detection by predators. Fish with colors in the middle of the spectrum, particularly blue, appear to be less dependent on depth for concealment. This is likely due to the fact that blue fish are able to camouflage into their surroundings at relatively any depth.

Modeling Light Transmission and Visibility

Applying the Beer-Lambert Law

It is evident that fish of certain colors rely heavily on depth for survival, as it allows them to camouflage into the surrounding water. to visualize how fish visibility is affected by multiple external factors, a model was created to show how light intensity changes with respect to depth and temperature variations. In doing so, the Beer-Lambert Law was implemented, which describes the attenuation of light as it travels through a medium. As stated previously, the equation is given by:

$$I_z = I_o e^{-k_{d(PAR)} * Z} \quad (3)$$

Where I_z represents the light intensity at depth z, I_o represents the light intensity at the surface of the water, and $k_{d(PAR)}$ is the diffuse attenuation coefficient with respect to photosynthetically active radiation.

By incorporating this equation into an interactive Shiny application, a tool was created that allows users to explore how light intensity changes under different conditions. The app enables users to set a maximum depth for the x-axis, select a wavelength of interest, adjust water temperature to observe its effect on light penetration, and choose a specific depth to compare normal and altered light intensities based on the selected temperature changes.

The first step in constructing the interface involved gathering data on solar irradiance and diffuse attenuation values by wavelength. Initial light intensities were obtained from the solar irradiance climate data record developed by NOAA's Climate Data Record Program in collaboration with the Laboratory for Atmospheric and Space Physics (LASP) and the Naval Research Laboratory (NRL). This data set, published by Coddington et al. (2016), provides consistent and scientifically validated records of both total solar irradiance and solar spectral irradiance from 1610 to the present. It also incorporates modeled variations due to sunspot activity and other solar phenomena and is archived by NOAA's National Centers for Environmental Information.

Table 7

Spectral Light Properties: Initial Solar Irradiance and Diffuse Attenuation Coefficients by Wavelength

Wavelength (nm)	Initial Light Intensity (I_0)	Diffuse Attenuation Coefficient ($k_{d(PAR)}$)
200	0.006923707	3.14
210	0.020296489	2.05
220	0.047510172	1.36
230	0.043975909	0.968
240	0.042686246	0.754
250	0.057021376	0.588
...	...	...

Note. This table displays the initial light intensity values at the ocean surface (I_o) and the corresponding diffuse attenuation coefficients ($k_{d(PAR)}$) for specific wavelengths ranging from 200 to 250 nanometers. I_o values represent spectral solar irradiance derived from NOAA's Solar Irradiance Climate Data Record, while $k_{d(PAR)}$ values are based on measurements from Smith and Baker (1981), which quantify how rapidly light diminishes with depth due to absorption and scattering in clear ocean water. The full table contains the initial light intensity and diffuse attenuation coefficient values for wavelengths up to 800 nm (not depicted).

The above solar irradiance data were matched to their corresponding wavelengths and applied to Equation 3 (the Beer-Lambert-Law) to determine the initial light intensity values

entering the ocean. The term solar irradiance refers to the total power per unit area hitting a surface at a particular time, measured in watts per square meter (Wm^{-2}). Total solar irradiance includes the sun's exerted energy across all wavelengths as it reaches the Earth's upper atmosphere. In contrast, solar spectral irradiance describes the amount of energy exerted across all wavelengths of the electromagnetic spectrum. Solar spectral irradiance provides insight into the amount of energy emitted at each wavelength and is measure in watts per square meter per nanometer ($Wm^{-2} \cdot nm^{-1}$), indicating the intensity of energy at each individual wavelength.

In order to obtain the values of the diffuse attenuation coefficients ($k_{d(PAR)}$), a foundational study by Smith and Baker (1981) was referenced. Their study deployed a UV submersible spectroradiometer into the ocean to measure light attenuation in relatively clear natural waters. Their work focused primarily on the spectral ranges between 300 and 400 nanometers, as well as a broader range from 300 to 800 nm. Their findings were uploaded into a dataset which includes a plethora of information. Spectral absorption coefficients were included, which quantify the amount of light absorbed by seawater at various wavelengths. Molecular scattering coefficients were also included, anointing for the scattering of light with respect to the number of water molecules. Finally, diffuse attenuation coefficients were also included, describing how light intensity diminishes as it penetrates deeper into the water, which can be affected by both absorption and scattering. Smith and Baker applied radiative transfer theory to derive the above mentioned optical properties, which allow for a highly accurate estimate of light's behavior in both pure and natural water conditions.

With both the irradiance and attenuation data obtained and analyzed, R was further used to model the variation of light intensity with respect to depth in order to create a dynamic interface, utilizing the *Shiny* package. The interactive tool allows users to adjust specific

parameters and observe how environmental changes, particularly those related to climate change, might influence underwater light penetration. Through this framework, it becomes possible to explore how visibility of color changes over time and how such shifts might impact marine organisms that rely on depth and camouflage for survival.

Building a Shiny App for Visualization

To explore how light intensity changes with respect to depth across different wavelengths and under varying environmental conditions, an interactive interface using the *Shiny* package in R was developed. This tool will allow users to visualize and compare light attenuation patterns in water based on real-world data, as presented in Table 7. The code for creating the interface begins by loading necessary packages such as *Shiny* for building the web interface, and *ggplot2* for visualizing the results within the app. Additionally, imported data including initial light intensities (I_o) and diffuse attenuation coefficients (k_d) for specific wavelengths are necessary to include.

```
> ui <- fluidPage(
     titlePanel(“Light Intensity at Depth”),
     sidebarLayout(
          sidebarPanel(
               numericInput(“depth”, “Enter Max Depth (m):”,
                            value = 50, min = 0, step = 1),
               selectInput(“wavelength”, “Select Wavelength (nm):”,
                            choices = df.shineData$wavelength_nm,
```

```
                              selected = df.shineData$wavelength_nm[1]),
                sliderInput("temperature",
                            "Select Water Temperature (°C):",
                            min = 0, max = 40, value = 20, step = 0.1),
                numericInput("compareDepth", "Depth to Compare (m):",
                             value = 20, min = 0, step = 1)
            ),
            mainPanel(
                plotOutput("intensityPlot"),
                textOutput("differenceOutput")
            )
        )
)
```

The shiny app is structured using the `fluidPage()` function, which creates a flexible layout that adapts to different screen sizes. Within this layout, the `titlePanel()` function was also used to provide a clear title for the interface: "*Light Intensity at Depth*." This gives users an immediate understanding of the app's purpose.

The core of the user interaction takes place in the `sidebarLayout()`, which consists of two main sections: a `sidebarPanel()` for inputs and a `mainPanel()` for outputs. Inside the `sidebarPanel()`, several interactive input controls are defined. `numericInput("depth", "Enter Max Depth (m):", value = 50, min = 0, step = 1)` allows users to set the maximum depth for the light attenuation calculation. This is important because it defines the vertical range over which light penetration is modeled. `selectInput("wavelength",`

`"Select Wavelength (nm):", choices = df.shineData$wavelength_nm, selected = df.shineData$wavelength_nm[1])` enables users to choose a specific wavelength of light. Since different wavelengths penetrate water to different extents, this option is crucial for exploring how spectral variations influence underwater visibility. `sliderInput("temperature", "Select Water Temperature (°C):", min = 0, max = 40, value = 20, step = 0.1),` allows the user to simulate how different temperatures might affect light attenuation. Although temperature does not directly alter k_d, it can influence variables like chlorophyll levels or salinity that do contribute to attenuation. `numericInput("compareDepth", "Depth to Compare (m):",value = 20, min = 0, step = 1)` provides an additional reference depth so that users can isolate and compare light intensity at a specific point in the water column. The `mainPanel()` holds the output components. `plotOutput("intensityPlot")` generates a graph of light intensity as a function of depth, visualizing how it rapidly diminishes with increasing distance from the surface. `textOutput("differenceOutput")` displays a calculated comparison of light intensity between the surface and the selected comparison depth, offering users an intuitive understanding of how much light is lost by that point.

Altogether, this Shiny interface not only illustrates the physical principles behind the Beer-Lambert Law, but it also makes the scientific model accessible and exploratory. Users can interact with real data and see how factors such as depth, wavelength, and temperature influence underwater light environments: factors that ultimately affect the visibility and survival strategies of marine organisms. This interactive framework can also be adapted for climate modeling to assess how future ocean conditions may alter light penetration and its ecological consequences.

The “server” portion of the Shiny app defines the logic that responds to user inputs and dynamically generates both visual and textual outputs based on those inputs. This part is essential because it processes the data and calculations needed to model light attenuation in the ocean and reflect how environmental conditions affect it.

The function `server <- function(input, output)` begins by defining the reactive output for the light intensity plot using `renderPlot()`. First, the server filters the data to match the user’s selected wavelength. This ensures that all calculations use the correct values of initial light intensity (I_0) and the diffuse attenuation coefficient(k_d) for that specific wavelength, using the following lines of code:

```
> selectedRow <- df.shineData[df.shineData$wavelength == input$wavelength, ]
> I_o <- selectedRow$I_o
> baseline_K_d <- selectedRow$k_d
```

Next, the code adjusts k_d based on the user-selected water temperature. While temperature does not directly influence light attenuation, it does affect all the factors that comprise it. As a result, a hypothetical temperature adjustment is included here to simulate possible environmental effects, such as increased particulate matter or biological activity in warmer waters. The adjustment formula used is:

```
> temp_factor <- 0.02 * (input$temperature - 20)
> adjusted_K_d <- baseline_K_d + temp_factor
```

The server then generates a sequence of depths using `seq(0, input$depth, length.out = 100)`, creating a smooth curve for light intensity across the selected depth range. Two intensity curves are computed: one using the baseline k_d and another with the temperature-adjusted k_d, both based on the exponential decay formula derived from the Beer-Lambert Law:

```
> baseline_intensity <- I_o * exp(-baseline_K_d * depth_seq)
> adjusted_intensity <- I_o * exp(-adjusted_K_d * depth_seq)
```

These values are then assembled into a data frame and visualized using ggplot2. The plot clearly displays how light diminishes with depth under baseline and adjusted conditions, allowing users to compare the effects of temperature:

```
> ggplot(plot_data, aes(x = Depth, y = Intensity, color = Curve)) +
      geom_line(size = 1.2) +
...
```

In addition to this plot, a text output is rendered via `renderText()` to provide a numerical comparison at a user-specified reference depth. The same attenuation formula is used to compute the intensity values at this depth, both with and without temperature adjustment:

```
> baseline_intensity <- I_o * exp(-baseline_K_d * compareDepth)
> adjusted_intensity <- I_o * exp(-adjusted_K_d * compareDepth)


> difference <- baseline_intensity - adjusted_intensity
```

This difference in light intensity is then displayed in the app as a sentence below the graph, helping users interpret the impact of environmental changes at a specific point in the water column.

Together, this server-side logic brings the user interface to life. It allows for a hands-on exploration of how physical parameters like wavelength, depth, and temperature influence the underwater light environment. The ability to visualize and quantify these changes supports deeper understanding of real-world implications, such as the effectiveness of camouflage in marine species or potential effects of climate-driven temperature shifts on light availability at specific depths.

The Shiny app described above provides an interactive visualization of how light intensity changes with ocean depth and temperature across different wavelengths. Users can modify inputs such as depth, wavelength, and water temperature to observe how these factors affect light penetration in the ocean. A numerical comparison at a user-defined depth is also displayed, helping users better understand the relationship between temperature-induced attenuation and light availability.

To explore the app directly, it can be accessed online at the following link: https://0cqnfa-katerina-poulathas.shinyapps.io/justtheapp/

This tool serves as a powerful companion to the analysis presented in this thesis, offering both scientific insight and an accessible user experience for those interested in ocean optics, climate change, and underwater ecology.

Results and Discussion

Interpreting Results from Shiny App

This interactive approach allows for the visualization of various scenarios, demonstrating how light attenuation varies across different wavelengths and depths. Each color is associated with a specific wavelength, and typical habitat depths of fish species can be used to observe how changes in light intensity affect their visibility. The reference values for each wavelength are:

Table 8

Reference Values to be Applied to Shiny App

Color	Wavelength(nm)	Typical Depth of Fish for Color (m)	Difference in Light Intensity (Wm^{-2})
Red	700	350	0
Orange	610	181.5	0
Yellow	570	110	3e-04
Green	550	148	1e-04
Blue	470	200	0.0625
Violet	420	680	0

Through further experimentation with the app, it can be observed that the largest gap between normal and altered light intensity occurs for light at 450 nm at 30 meters. At this point, a 2°C increase in temperature significantly reduces light penetration, decreasing intensity by 0.8491. This suggests that even small temperature changes can have a noticeable impact on underwater light environments, potentially altering how marine organisms perceive their surroundings.

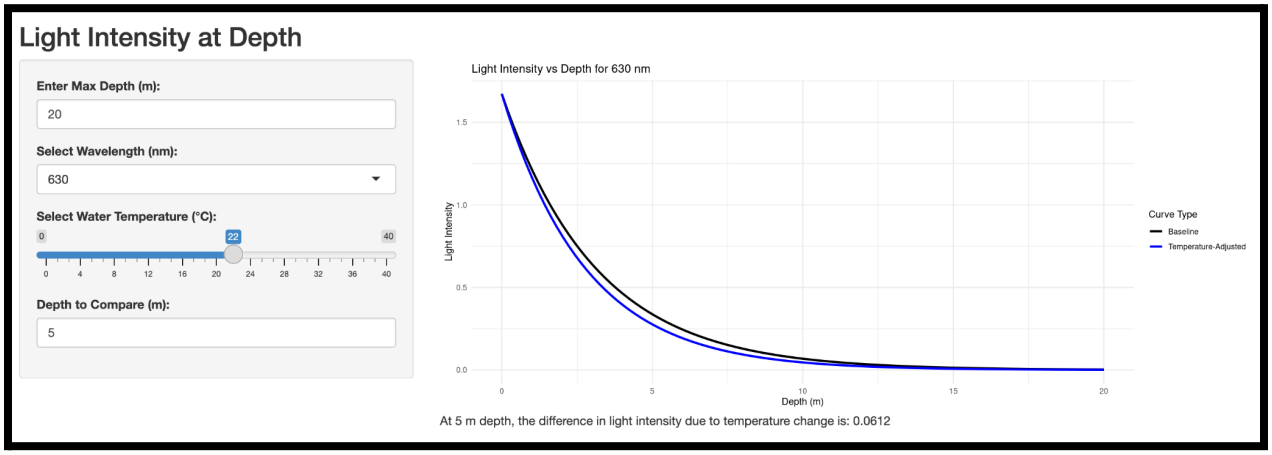
Applying the Shiny App to a Specific Circumstance

While the *Shiny* app can be useful to visualize the change in light intensity for specific wavelengths with respect to temperature, it is also important and interesting to observe how the interface can be applied to specific situations.

For example, say a researcher wanted to test the possible effects of climate change on the location of the Hawaiian Spikefish. A quick search into the dataset that is stored in the variable named "my_fishies" (created in this thesis and derived from *FishBase*), will provide the user with relevant information on the Hawaiian Spikefish, including its color categorization. In this case, the Hawaiian Spikefish is categorized as "red". Red corresponds to wavelengths of about 630 nm. When this data is entered into the shiny app, an exponential decay graph is formed. If the temperature of the ocean water is increased by just two degrees celsius, the light intensity will be projected to decrease by 0.0612 Wm^{-2} at a depth of 5 meters. This ultimately shows that wavelengths corresponding to the color "red" will not penetrate as deep in the water with rising temperatures. Although the difference in light intensity seems small, it is extremely significant and can pose a threat to the survival of organisms who rely on camouflage for survival.

Figure 12

Difference in Light Intensity for Hawaiian Spikefish



Note. Implementation of the *Shiny* app for the Hawaiian Spikefish at 630 nm from 20 to 22 degrees celsius increase in temperature at a depth of 5 meters below the surface shows a decrease in light intensity by 0.0612 Wm^{-2}.

Conclusion

Summary of Findings

This thesis was able to answer many questions. First, a dataset was created using information found in *FishBase* to include a complete list of 9,806 fish, as well as their corresponding genus, species, common name, depth ranges, pelagic region, and color. With the help of R, *rfishbase*, and numerous other packages and functions, a statistically significant relationship between fish color and depth was determined. The results showed that fish colored red and violet typically frequented deeper waters, as opposed to fish colored orange, yellow, and green. A possible explanation for this finding is that blue fish do not rely on living at depths below their point of "invisibility". Instead, they can remain at virtually any depth and perceivably blend into their surroundings. Fish that are red in coloration, however, can not blend into the water at any depth. Instead, they rely on extreme depths to appear camouflaged, which protects them from predators.

Climate change does not discriminate, as it affects all ecosystems. The effect of climate change on water clarity and light penetration was studied extensively in this thesis. Research has shown that increased temperatures correspond to an increase in phytoplankton, which ultimately increases chlorophyll levels in the ocean. An increase in chlorophyll will not only make the ocean appear more green in hue, but it will also affect the penetration of light in the ocean. Due to an increased number of floating particulate matter, light will not be able to penetrate perpendicularly to the water, and therefore not be able to reach max depths. Instead, floating metter reflects light, causing light to not be able to penetrate as deep. With increased floating particulate matter due to climate change, light will not be able to penetrate nearly as deep, which

in turn will also affect the depths at which colors will be perceived underwater. Simply put, The maximum depths in which colors can be perceived will decrease with increased temperatures.

Finally, this thesis applied all the above learned knowledge into a single interactive interface that allows users to visualize the effects of climate related changes on light intensity in the ocean. The *Shiny* application created in R allows users to select a wavelength from a list of 200 to 800 nm, alter the depth of interest, as well as increase or decrease temperature. It can be seen that an increase in temperature shows a significant change in light intensity for all wavelengths. With more significant increases in temperature, there is a large decrease in light intensity in the ocean.

All of these findings present how climate change affects the depths at which fish frequent, which could ultimately alter entire marine ecosystems.

Limitations and Future Research Directions

While considerable advancements have been made in understanding how light and color behave underwater, there continue to remain important limitations in the available research, particularly regarding biological applications. One key limitation is the lack of detailed spectral data linking specific fish species to their coloration and corresponding wavelength properties. While general patterns of visibility and absorption by wavelength are well established, there is a scarcity of comprehensive data on the precise wavelengths associated with the color of individual fish.

This gap limits our ability to accurately model or predict how visible certain fish may be at different depths. For example, a fish with red pigmentation may appear nearly invisible at

greater depths due to red light's rapid absorption, but without specific spectral measurements tied to that species, such inferences remain generalized.

Future research could benefit from collecting high-resolution reflectance and absorption data for a wide range of marine species, particularly focusing on how their coloration corresponds to the optical properties of their environment. Spectrophotometric analysis of fish scales and skin, in combination with environmental light data, could provide a clearer picture of visibility and camouflage strategies in marine life. Additionally, the integration of *rfishbase* and other marine biodiversity databases with color and depth-specific ecological and evolutionary models regarding fish coloration and its role in camouflage and survival.

Fish location tracking has been used in the past, especially for monitoring the migration patterns of fish latitudinally. Similar techniques should be implemented on a larger scale to track the longitudinal shift of specific fish species over a period of time. Location data, as well as complete spectral measurements of fish would provide scientists with a complete picture of exactly how fish of specific colors rely on depth for survival, as well as how their depths may change over the years due to climate change.

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