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The Effects of Laser Eye Protection on Color Recognition and Discrimination

Sherisse Melanie Pierre

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by

Sherisse Melanie Pierre

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The undersigned committee hereby recommends that the attached document be accepted as fulfilling in part the requirements for the degree of Master of Science in Aviation Human Factors. "The Effects of Laser Eye Protection on Color Recognition and Discrimination," a thesis by Sherisse Melanie Pierre.

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Deborah Carstens, Ph.D.
Graduate Program Chair and Professor
College of Aeronautics
Committee Chair

____

John Deaton, Ph.D.
Director of Research and Chair, Human Factors Program
College of Aeronautics

____

William Arrasmith, Ph.D.
Professor
College of Engineering

____

Korhan Oyman, Ph.D.
Dean and Professor
College of Aeronautics

Abstract

Title: The Effects of Laser Eye Protection on Color Recognition and Discrimination

Author: Sherisse Melanie Pierre

Advisor: Deborah Carstens, Ph.D.

The number of reported laser strikes on aircraft has increased over the years. Laser strikes pose a threat to safety and thus, warrant attention and mitigation efforts. Laser Eye Protection (LEP) is one mitigation method available to pilots; however, LEP can affect a person's color vision. When wearing the LEP pilots should be able to retain sufficient color recognition and discrimination abilities. This exploratory study investigates the effect of LEP on color recognition and discrimination of four colors, red, blue, green, and amber, using a sample of 90 participants. When using the LEP the majority of participants were able to identify or recognize the correct color, but color discrimination between different shades of the same general color proved to be less accurate. Of the four investigated colors, results suggest that color recognition of amber was the most affected by LEP.

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List of Abbreviations

Abbreviation	Explanation
AC	Advisory Circular
ANSI	American National Standards Institute
CFR	Code of Federal Regulations
FAA	Federal Aviation Administration
FBI	Federal Bureau of Investigation
FIT	Florida Institute of Technology
IRB	Institutional Review Board
LEP	Laser Eye Protection
LEP1-RG	Laser protection eyewear used in the study that blocks red and green laser light
LEP2-RGB	Laser protection eyewear used in the study that blocks red, green, and blue laser light
LIA	Laser Institute of America
MFD	Multi-function Display
NAS	National Airspace System
PFD	Primary Flight Display
TNO	Netherlands Organization for Applied Scientific Research
USC	United States Code (Federal Law)
UV	Ultra violet

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Chapter 1
Introduction

Problem Statement

Within recent years, the number of reported laser strikes on aircraft has increased dramatically. Fortunately, to this day, there has not been an aviation accident resulting from a laser strike incident; however, laser strikes pose a threat to safety and thus, warrant attention and mitigation efforts. A laser strike that enters the cockpit of aircraft (laser cockpit illumination) is a distraction and can temporarily blind pilots during the most critical phases of flight. This is a hazard that has the potential to change an ordinary approach and landing into a disastrous accident.

Laser Eye Protection (LEP) is one mitigation method available to pilots. Available LEP designed for pilots usually come in the form of spectacles, similar to sunglasses. LEP can be tailored to protect against specific colors. Blocking laser light of one singular color is a simple process for manufacturers; however producing eyewear that is capable of blocking laser light of multiple colors, while still allowing acceptable color recognition and discrimination is more difficult. For some industrial purposes, laser protection eyewear is a matter of blocking almost all of a single color of light but for aviation, it is a much more delicate balance.

When developing LEP designed to be marketed to pilots, the developers and manufacturers must take into consideration that pilots when wearing the LEP should still retain sufficient color recognition and discrimination abilities. Pilots must be able to discern differences between items on the aircraft's cockpit display as well as near accurately perceive the correct color.

Many instruments and gauges in an aviation cockpit utilize color differences to indicate a different status, mode, position, or quantity. For example, looking at the traditional airspeed indicator, color is used to delineate airspeed limitations. Colored lights on an airfield also identify different surface areas and are also used to identify the type of airport. In the event of a radio communication failure, air traffic control towers have the ability to display light gun signals which usually may include three colors; red, green, and white. These are a few examples of the importance of color vision in aviation. Any protection eyewear that a pilot may use should not greatly affect his or her ability to discern colors of cockpit displays, airport lighting, or other colors.

Purpose Statement

The aim of this study is to investigate the effects of LEP on color recognition and discrimination. To investigate these effects, two different types of

LEP that were designed for pilots and are currently available on the market were used alongside a pair of clear protection eyewear with no special laser blocking capabilities. These materials were used to investigate the LEP's effects on color recognition and discrimination and to make comparisons among the eyewear.

Rationale

Due to the rising number of aviation laser strikes, and the difficulty in apprehending individuals who maliciously aim lasers at aircraft, pilot controlled mitigation methods are necessary. A pilot can be equipped with an LEP device as a proactive measure for protection against laser cockpit illuminations. The FAA recommends to "[p]erform human factors studies to investigate whether providing pilots with Laser Eye Protection (LEP) is a practical means to mitigate certain potential laser hazards. These studies should also address the effects of LEP on color vision, visual acuity, and operational performance" (Nakagawara, Wood, & Montgomery, 2006, p. 7). This study investigates the effects of LEP on two components of color vision; color recognition and color discrimination.

Operational Definitions

For the purposes of this study, it is important to discuss how some of the variables were defined in terms of the study. This increases ease of understanding, provides clarity to readers, and establishes the basis upon which the conclusions and comparisons are drawn.

Color recognition

Color recognition is the ability to identify a color or hue (for example, the participant can identify a red color-block is red, as opposed to blue). For the purposes of this study, color recognition will be measured by the number of correct color identifications (red color-block identified as red) during the Color-block test study instrument.

Color discrimination

Color discrimination is the ability to see differences between different colors and choose one specific color from a group of colors (for example, choosing a specific shade of red from a group of 12 other colors, including other shades of red). Color discrimination will be measured by the number of correct color and shade identifications (correct color-block selection) during the Color-block test study instrument.

Laser eye protection (LEP)

For the purposes of this study, LEP refers to eyewear designed to block established amounts of laser light of different colors. There will be two LEP devices used in this study.

Clear protection eyewear

For the purposes of this study, clear protection eyewear refers to a pair of protective eyewear with clear polycarbonate lenses that do not have special laser blocking capabilities. This eyewear was designed to protect the wearer's eyes during some potentially hazardous activities such as shooting, hunting, and archery.

Experience with LEP

For the purposes of this study, experience with LEP will be defined as undergoing five minutes of using the LEP with minimal restrictions while viewing a series of different color-blocks that will appear during the Color-block test.

Background

The number of reported aviation laser strike and cockpit illumination incidents has been increasing. There were 385 reported incidents in 2006 and 3,960 reported incidents in 2013 (FAA, 2014a). The FAA notes that the "temporary visual impairment, distraction, disorientation, and discomfort" associated with laser strikes can result in potentially hazardous conditions and situations (Nakagawara et al., 2006, p. 1).

One method to mitigate the effects of a laser cockpit illumination is the use of LEP devices. Using an LEP can provide a pilot with protection from the negative effects of a cockpit laser illumination; however, LEP devices are not without drawbacks. Due to the methods used to block laser light, LEP devices affect a wearer's color recognition and discrimination abilities. Color recognition and discrimination in aviation is vital. Pilots must be able to correctly identify different colors both inside and outside of the cockpit (Palakkamanil & Fielden, 2015). Any protection used by pilots to mitigate the effects of a cockpit laser illumination should still allow the pilots the ability to recognize and discriminate between different colors. Therefore, LEP devices designed for pilots provide a delicate balance of blocking laser light, while still allowing the pilot to perceive near accurate color (Dykes et al., 2000).

Research Questions and Hypotheses

Research Questions

This study will be governed by the following research questions:

RQ1: What is the effect of laser eye protection on color recognition?

RQ2: What is the effect of laser eye protection on color discrimination?

RQ3: Which color from those investigated is most greatly affected by laser eye protection?

Hypotheses

Null Hypothesis 1.

H_{01}: Laser eye protection has no significant effect on color recognition.

Alternative Hypothesis 1.

H_{A1}: Laser eye protection has a significant effect on color recognition.

Null Hypothesis 2.

H_{02}: Laser eye protection has no significant effect on color discrimination.

Alternative Hypothesis 2.

H_{A2}: Laser eye protection has a significant effect on color discrimination.

Null Hypothesis 3.

H_{03}: The laser eye protection's effects on color recognition and discrimination will be the same for all colors.

Alternative Hypothesis 3.

H_{A3}: Color recognition or discrimination of at least one color will be significantly more affected by the laser eye protection.

Assumptions

One assumption of this study is that the participants are aware of their color vision history and have normal color vision. An individual who has a known color deficiency will not be eligible to participate in the study. While the study does test for common color vision deficiencies, all possible deficiencies are not detected by the test.

Another assumption of the study is that there will be honest participation from participants. The study assumes that participants will report their demographic data honestly and that participants will pay attention to the pre-test presentation and Color-block test. While participants may be discouraged from guessing, there is no way to eliminate potential participant guessing during the study.

The study also relies on honest manufacturer specifications and assumes that the LEP devices work to block and transmit light in the specified proportions as designated by the manufacturer.

For statistical analysis, a Chi-square test will be used and thus this study also makes the assumptions associated with Chi-square testing. These assumptions include that the expected frequency in any cell of the contingency table is not less than five, and that the observations are independent of each other (Ary, Jacobs, & Sorensen, 2010).

Chapter 2
Literature Review

Introduction

Aviation laser illumination incidents pose a threat to aviation safety and flight crew health. With cockpit laser illuminations, pilots can be distracted from their duties during one of the most critical phases of flight (Nakagawara et al., 2006). The flight crew may also be susceptible to eye damage due to direct cockpit laser illuminations. To this date, there have been no major accidents resulting from an aviation laser illumination incident, but this threat should be mitigated to prevent such an accident (Nakagawara et al., 2006). One method that can be used in preventing these types of accidents is facilitating public awareness. Pilots, especially general aviation pilots, may not be aware of the growing threat and the possible associated hazards, and may not know what to do in the event that a laser illumination is experienced (Nakagawara, Montgomery, & Wood, 2011a). Members of the general public may not know that it is a federal violation, punishable by a fine or imprisonment, to point a laser at an aircraft, and they may also be unaware of the dangers it poses to pilots and everyone on board (FAA Modernization and Reform Act of 2012).

Another method that can be employed to mitigate the threat is LEP. LEP can protect the eyes of flight crews, and also reduce the negative effects associated with cockpit laser illuminations, allowing flight crews to be less impaired should they encounter a laser illumination in-flight. While LEP may provide the protection necessary to shield eyes from laser light, the methods used to block the laser light may result in changing the appearance of colors in the scene viewed. This has the potential to affect the wearer's color recognition and discrimination abilities (Kuyk, Brockmeier, Morin, LaFrance, & Foutch, 2010). This chapter investigates the need and potential impact that LEP can have on the aviation industry.

Aviation Laser Illuminations: The Trend

In the early 1990's, many of the laser illumination incidents were attributed to public laser light demonstrations for amusement and entertainment (Nakagawara et al., 2006). This prompted the revision of FAA Order 7400.2, "Procedures for Handling Airspace Matters" in 1995, in which the FAA provided guidance and restrictions on lasers projected into the National Airspace System (NAS). Today, the most recent revision of that FAA Order, Order JO 7400.2K, includes a description and depiction of laser protected areas and conditions under which lasers may be used in the NAS (FAA, 2014b).

Prior to 2005, there was no official avenue or portal to report aviation laser illumination incidents, and so many incidents went unreported. According to Nakagawara, Montgomery, and Wood (2011b) during the end of the year 2004, there was a spike in the number of laser strike incidents reported. This prompted the publication of FAA Advisory Circular (AC 70-2), “Reporting of Laser Illumination of Aircraft” which gave aviation personnel an official reporting tool and procedure (Nakagawara et al., 2011b). The number of reported aviation laser strike incidents has still been on the rise since 2006, increasing from 385 reported incidents in 2006, to 3,960 reported incidents in 2013 (FAA, 2014a). The FAA attributed the increase to several factors including “greater awareness by pilots to report laser incidents” and “the availability of inexpensive laser devices on the Internet” (FAA, 2014a, para. 4). One of the FAA’s responses to the drastic increase was to investigate more of the laser strike reports and more firmly enforce the regulations. The FAA established regulations for authorized outdoor laser operations in the NAS as published in FAA Order JO 7400.2K (Nakagawara et al., 2006; FAA, 2014b). These regulations have helped to cut down on inadvertent aviation laser strikes from planned outdoor laser shows and demonstrations; however, the laser strike problem continues to grow as the majority of the laser strike incidents are due to intentional acts by random individuals with "portable, hand-held laser devices" (Nakagawara et al., 2006, p. 6). The problem of laser illumination incidents is not restricted to only the United States. Waggel and Hutchinson (2013) mention that in 2011, 2300 aviation laser strikes were reported in the United Kingdom, and Palakkamanil and Fielden (2015) mention that 461 aviation laser strike incidents occurred in Canada in 2013.

In 2006, the FAA published "A Review of Recent Laser Illumination Events in the Aviation Environment" which analyzed reported aviation laser strikes in the 13 month period January 2004 to January 2005. In the studied time period, there were 90 reported laser strikes, of which 53 (59%) involved commercial aircraft, 62 (69%) involved green laser light, and 13 (32%) resulted in "visual impairment or distraction" (Nakagawara et al., 2006, p. 6). The FAA notes that the "temporary visual impairment, distraction, disorientation, and discomfort" associated with laser strikes can result in potentially hazardous conditions and situations (Nakagawara et al., 2006, p. 1). Nine out of the 13 incidents that resulted in visual impairment or distraction occurred during the approach to landing phase; one of the most critical phases of flight. One of these incidents, which also involved green laser light and a commercial aircraft, resulted in a retinal injury and the Delta Airline pilot was unable to return to work for three weeks (Nakagawara et al., 2006).

Nakagawara et al. (2011a) conducted the study “Laser Illumination of Flight Crewmembers by Altitude and Chronology of Occurrence” in which they examined laser illumination incident trends over the five-year period, January 2004 to December 2008. The research suggested that aviation laser strikes occurred more frequently in the months of November and December, and on weekends, especially Sundays. The times between 1900 (7:00 pm) and 2300 (11:00 pm) were the most popular times in which laser strikes occurred (Nakagawara et al., 2011a). This study agreed with the FAA review (Nakagawara et al., 2006) in finding that laser strikes on commercial aircraft accounted for the majority (73%) of the incidents (Nakagawara et al., 2011a). The results also suggested that low flying aircraft, below 6000 feet, were more likely to encounter a laser strike. This is of particular concern since lower altitude flight usually involves more critical phases of flight (takeoff and landing) and the proximity to obstacles and terrain make pilot distraction even more hazardous (Nakagawara et al., 2011a).

It has proven to be quite difficult for the FAA and law enforcement to locate individual regulation violators who intentionally illuminate aircraft with lasers. In the 13 month time period of the FAA review, only three arrests were made. One of these arrests resulted from the fact that the violator struck a law enforcement helicopter with a green laser while that aircraft was on a laser strike investigation mission (Nakagawara et al., 2006). Nakagawara et al. (2011a) suggest that a coordinated effort between local law enforcement and laser illumination incident reporting systems can help in leading to more violator arrests.

In 2012, the FAA made formally reporting laser illumination incidents easier by developing a "Laser Beam Exposure Questionnaire" that pilots can fill out upon landing after having encountered a laser illumination (AC 70-2A, 2013). This questionnaire can be completed electronically or by hand, and can be submitted either electronically, by mail, or by fax. There is even a mobile application version of the questionnaire. Improving the available reporting systems for aviation laser illuminations is one of the measures the FAA has taken to mitigate the threat. According to AC 70-2A, the FAA in conjunction with the Federal Bureau of Investigation (FBI), local law enforcement, and other government agencies work together in order to take "immediate action to safeguard flights against these unauthorized illuminations and expeditiously locate the source of unauthorized laser transmissions" (p. 1).

The Code of Federal Regulations, Title 14, section 91.11 states that "[n]o person may assault, threaten, intimidate, or interfere with a crewmember in the performance of the crewmember's duties aboard an aircraft being operated." In a public memorandum, the FAA Office of Chief Counsel explained that pointing a laser at an aircraft constitutes as a violation of 14 CFR § 91.11 because the laser beam can distract and visually impair the flight crew "which could compromise safety by adversely interfering with the ability of aircrews to carry out their responsibilities" (Griffith, 2011; AC 70-2A, p. 1). Thus, according to the FAA Modernization and Reform Act of 2012, violators of this regulation can be subject to civil penalties, including imprisonment for up to five years. However, the FAA recently issued an amendment, Appendix H, to the FAA Compliance and Enforcement Program, Order 2150.3B (FAA, 2016a). Due to the fact that the number of aviation laser illumination incidents continued to increase, the FAA Acting Administrator concluded "that a special emphasis enforcement program is warranted for violations of 14 C.F.R. §§ 91.11, 121.580, 125.328, and 135.120" (p. 1). The amendment outlines the legal actions that should be taken against individuals who violate these sections by pointing a laser at an aircraft. The actions include:

> "2. A single, first-time, inadvertent or non-deliberate violation by an individual generally warrants a civil penalty in the moderate range ($2,200-$4,399).
>
> 3. For a deliberate violation by an individual not holding an airman certificate, the FAA may seek a civil penalty up to the statutory maximum of $11,000 per violation under 49 U.S.C. § 46301(a)(5)(A).
>
> 4. For a deliberate violation by an airman certificate holder, regardless of whether the airman was exercising the privileges of his or her certificate at

the time of the violation, the appropriate sanction generally is revocation of the airman certificate. A civil penalty in the maximum range may be appropriate in addition to certificate revocation" (pp. 1-2).

Lasers and the Human Eye

Light Amplification by Stimulated Emission of Radiation (LASER) involves a process that results in a monochromatic and concentrated beam of light (Harris, Lincoln, Amoroso, Stuck, & Sliney, 2003; Nakagawara et al., 2006). Over the years, since the 1960's, the use of lasers has been integrated into many industries including the medical and entertainment industries, and has even been integrated into military operations (Harrington & Wigle, 2004). The Laser Institute of America (LIA) has published guidance information on classification criteria, training requirements, and use restrictions on the different classes of lasers (ANSI Z136.1-2007, 2007). Nakagawara et al. (2008) explain that the U.S. Food and Drug Administration's Center for Devices and Radiological Health have mandated that manufacturers of commercial laser devices "must classify their laser products as Class I, II, IIIA, IIIB, or IV," label them appropriately, and produce "a report showing that requirements of compliance standards are met" (p. 519). Class I lasers are deemed to be generally not injurious to health, while Class IV lasers are very dangerous and "capable of irreversible eye damage" (Scollo, Herath, & Lobo, 2014, p. 220). Laser device manufacturers and commercial users are likely to follow the guidance given and meet the specific requirements for their laser devices or laser operations; however, individuals of the general public are less likely to take all the necessary precautions as stated in the guidance documents. Within more recent times, hand-held laser devices have become much more available to the general public (Nakagawara et al., 2006). Nakagawara et al. (2006) explain that the use of these “portable, hand-held laser devices” cannot be as easily restricted and controlled as those used in industrial settings and “no order or regulation can prevent thoughtless individuals, criminals, or terrorists from using lasers to interfere with the operation of law enforcement and emergency medical evacuation helicopters or private and commercial aircraft” (p. 2).

The human eye is sensitive to radiation (or light) in the visual spectrum (400 nm – 700 nm wavelengths) allowing one to see the colors that humans perceive; however, excessive direct exposure to these wavelengths can be injurious to the eye’s retina. High powered lasers have the ability to permanently damage one’s eyes and can even cause blindness and skin irritations (Scollo et al., 2014). While a brief exposure to low powered laser light may not permanently damage one’s eyes, it certainly creates a distraction and temporarily hinders vision (Nakagawara et al., 2006).

Human eyes undergo dark adaptation when in low light conditions which allows more light to enter the eye. The "pupillary dilation" of dark-adaptation makes the eye more sensitive to light and more susceptible to retinal damage in the event of a direct laser strike or illumination (Harris et al., 2003, p. 948). Nakagawara et al. (2006) explain that the human eye, when dark-adapted, is also more sensitive to the blue-green area of the visible light spectrum (507 nm), but the light-adapted eye "perceives yellow-green light (555 nm) more vividly" (p. 1). Due to these sensitivities to the green area of the visible spectrum, green laser light is the most detrimental to the human eye and is unfortunately also the most common color involved with aviation laser strike incidents (Nakagawara et al., 2006).

Effects of Laser Exposure

Scollo et al. (2014) produced a case study report covering a permanent retinal injury sustained from an accidental misfire of a Class IV industrial laser. The laser exposed worker reported a "sudden loss of vision in his right eye" and reduced vision capabilities in his left eye (Scollo et al., 2014, p. 220). After 18 months of treatment and periodical ophthalmologist visits, the worker regained better vision in the left eye, but minimal improvement in the right eye due to foveal damage (Scollo et al., 2014). This is an example of an injury caused by a very high powered laser which is not typical in aviation laser illumination incidents because industrial Class IV lasers are not readily available to the public.

Wyrsch, Baenninger, and Schmid (2010) covered a case study involving a teenage boy that “ordered a handheld laser pointer with green light on the Internet to use as a toy” (p. 1089). While playing with the device, his eyes were exposed to the green laser light several times, resulting in blurred vision and retinal damage. Wyrsch et al. (2010) stated that “his visual acuity was so poor in his left eye that he was only able to count fingers at a distance of 3 feet” (p. 1089). After four months of treatment, the boy’s vision improved, but there was evidence of foveal scarring and he did not regain his previous vision capabilities (Wyrsch et al., 2010). These authors also highlight the ease at which a Class III laser can be acquired and the similar outward appearances of harmless low powered laser pointers designed for presentations, and higher powered laser devices (Wyrsch et al., 2010).

It is difficult to determine the class of laser device involved in aviation laser illumination incidents because locating and apprehending the violators has proven to be difficult. Fortunately, there are very few aviation laser illumination incidents that result in any permanent damage. Glare, afterimage, flash blindness, and discomfort are the immediate concerns that affect a pilot that has endured a laser illumination (Nakagawara et al., 2011a; Nakagawara et al., 2011b). The FAA defines glare as “a temporary disruption in vision caused by the presence of a bright light within an individual’s field of vision,” flash blindness as “the inability to see, caused by bright light entering the eye that persists after the illumination has ceased,” and afterimage as “an image that remains in the visual field after an exposure to bright light” (2016b). These effects can be detrimental during the most critical phases of flight, since they distract and temporarily blind the pilot, and take attention away from flying the aircraft. On an approach or departure, when the aircraft is close to the ground, these types of distractions are particularly concerning. When executing a visual approach to landing, pilots must be able to see in order to make judgements and maneuvers to land the aircraft safely on the runway. Approach to landing is a dynamic critical phase of flight during which the pilot must monitor and adequately react to numerous environmental and spatial elements including wind gusts, airspeed, altitude, glide path, and other traffic (Nakagawara, Montgomery, Dillard, McLin, & Connor, 2004).

Higher intensity laser illuminations at lower altitudes during visual operations prove to have the most detrimental effect on pilot performance (Nakagawara et al., 2004). There is little room for error during these critical phases of flight, especially at night. During night time operations, a cockpit laser illumination would not only be a distraction, but would also add to the severity of the already existing possible visual illusions of nighttime operation (Nakagawara et al., 2006). Unfortunately, records show that most aviation laser strikes occur during the nighttime (Nakagawara et al., 2011b).

Laser Eye Protection and Color Vision

The FAA made several recommendations to help reduce or eliminate aviation laser strike incidents, including to "perform human factors studies to investigate whether providing pilots with LEP is a practical means to mitigate certain potential laser hazards" (Nakagawara et al., 2006, p. 7). There are several concerns surrounding LEP for pilots including its effects on "color vision, visual acuity, and operational performance" (Nakagawara et al., 2006, p. 7). When using LEP pilots must be able to retain substantial color discriminating abilities because many aspects of aviation rely on different colors (Palakkamanil & Fielden, 2015). Milburn, Neitz, Chidester, and Lemelin (2013) highlight that over the years, the use of color coding in aviation has increased due to "changing technology inside the cockpit, on air traffic control displays, and in the airport environment" (p. 1). The use of color can sometimes aid in communicating an instruction or intention without the need for verbal or written communication; however, color can only be a successful communication tool if both the sender and receiver can recognize and discriminate between colors (Milburn et al., 2013). With regards to airport lighting, lights of different colors may indicate a different surface or pavement area, for example, taxiway edge lights may be blue, while runway edge lights are generally white. A pilot must be able to differentiate between a runway and a taxiway for various safety reasons. At night, airport lighting plays an important part in surface recognition as it highlights the designated areas (Palakkamanil & Fielden, 2015).

Theories of Color Vision

One theory of color vision is the Young-Helmholtz trichromatic theory. According to Hurvich and Jameson (1957) and several other more recent studies, the Young-Helmholtz theory is a simple theory in which there are three types of cone photoreceptors in the eye's retina, each with a peak sensitivity in a different part of the visible spectrum; short, medium, and long wavelengths (Gegenfurtner & Kiper, 2003; Lucassen & Toet, 2006; Tolkova & Chernyshev, 2000). Each type of cone photoreceptor is sensitive to the majority of the visual spectrum but the peak sensitivity areas allow the different types of cones to be optimally stimulated by different wavelengths. Short wavelengths of light, near the blue area of the visible spectrum, stimulate S-cones; medium wavelengths, near the green area of the spectrum, stimulate M-cones; and long wavelengths, near the red area of the spectrum, stimulate L-cones (Hurvich & Jameson, 1957; Lucassen & Toet, 2006; Tolkova & Chernyshev, 2000). The Young-Helmholtz theory suggests that when individuals experience color, it is due to the stimulation of one or a combination of these cones (Hurvich & Jameson, 1957).

The other widely accepted theory of color vision is Hering's Opponent-Process theory. This theory suggests that there are three different pairs of visual processes that allow humans to perceive and discriminate between colors (Hurvich & Jameson, 1957). The three color pairs are red and green, blue and yellow, and black and white. The colors in each pair are considered to be "opponent" or opposite (Hurvich & Jameson, 1957). When one color is perceived the opponent color is considered to be inhibited. Hurvich and Jameson (1957) explain that these opponent pairs are the reason that "we may experience red-blues or green-blues but never yellow-blues, and we see yellow-greens or blue-greens, but never red-greens, and so on" (p. 386).

In both of these theories, cones as part of the visual system and visual processes allow humans with normal color vision to not only perceive color, but to discriminate between different colors as well (Gegenfurtner & Kiper, 2003).

Color Discrimination and Constancy

According to Jacobs (1981) and Mollon (1982) (as cited in Abrams, Hillis, & Brainard, 2007) color discrimination and constancy are two major functions that color vision supports. Abrams et al. (2007) define color discrimination as "the ability to determine that two spectra differ" (p. 1). Effective color discrimination allows for the use of color as a communication tool, but there are several factors that can affect an individual's color discriminating abilities including color vision deficiencies and lighting (Milburn et al., 2013; Royer, Houser, & Wilkerson, 2012). Royer et al. (2012) explain that color discrimination can be affected by the type of lighting present and the results of their study suggest that under light emitting diodes (LEDs), color discrimination proved to be more challenging for participants, especially near the yellow-green area of the visible spectrum, than the other types of lighting (tungsten-halogen and fluorescent lighting).

Abrams et al. (2007) define color constancy as "the ability to identify objects on the basis of their color appearance" (p. 1). The theory of color constancy suggests that an individual can "assign" a color to an object or recognize a color regardless of a change in the lighting condition (Gegenfurtner & Kiper, 2003, p. 193, Delahunt & Brainard, 2004). However, in some cases, visual illusions may make colors appear differently even though they are the same. Todorovic (2002) mentions simultaneous contrast, one such visual illusion in which objects of the same color are perceived differently due to differences in their background colors. Color constancy relies on color discrimination, because without discrimination every object may be identified as the same color (Abrams et al., 2007; Gegenfurtner & Kiper, 2003).

Color Discrimination and Sex

It is commonly thought that “women are capable of making finer visual color discriminations than men” (Reynolds, 1966). This may stem from the societal expectation that women may use color discrimination more often than men, especially when involving themselves in fashion and décor; traditionally feminine vocations (Reynolds, 1966; Rodriguez-Carmona, Sharpe, Harlow, & Barbur, 2008). In a study published in 1905, Nelson (1905) found that “men are clearly superior in the recognition of blue; and women are possibly superior in the recognition of yellow” (p. 279). Several, more recent studies have conflicting views about the effect sex has on color recognition and discrimination (Pardo, Pérez, & Suero, 2007; Reynolds, 1966; Rodriguez-Carmona et al., 2008). Pardo et al. (2007) suggest that there are significant differences in male and female color discrimination that can be explained by genetics on the X-chromosome. Rodriguez-Carmona et al. (2008), drawing from previous studies, suggest that females may have a wider vocabulary when identifying color, but their color sensitivity may not be any different from that of their male counterparts. Other studies including Pickford (1947) (as cited in Rodriguez-Carmona et al., 2008; Reynolds, 1966) conclude that once the results are controlled for genetic color-blindness prevalence, “there is no difference between males and females in color discrimination” (Rodriguez-Carmona et al., 2008).

Color Vision Testing in Aviation

To obtain an FAA Airman Medical Certificate without limitations, an individual must undergo and pass a color vision test. Aviation Medical Examiners, who administer the color vision tests, use one of the several testing techniques that the FAA has outlined in the "Guide for Aviation Medical Examiners" (2016b). An individual holding an FAA Airman Medical Certificate must demonstrate adequate color vision because color coding is heavily used in aviation (Milburn et al., 2013). For an individual to be considered as having adequate color vision, he/she must meet the FAA pass standards for the color vision test used (FAA, 2016b). Rodriguez-Carmona, O'Neill-Biba, and Barbur (2012) suggest that when testing for severity of color vision deficiency, the various color vision tests available are not always in agreement. Different color vision tests can indicate a different severity level of color vision deficiency for the same individual (Rodriguez-Carmona et al., 2012). Some tests also do not quantify a color vision deficiency, but merely indicate that a deficiency may be present (Delpero, O'Neill, Casson & Hovis, 2005). The most common color vision deficiency test uses "pseudoisochromatic plates (PIPs)" which identify red-green color deficiencies, but, traditionally, do not quantify the condition (Delpero, et al., 2005, p. 127). In their study, Rodriguez-Carmona et al. (2012) found that 8.43% of the participants with a protanope deficiency (weakness of color vision in the red spectrum) passed the 14-plate edition of the Ishihara color vision test according to the FAA standards. This suggests that, though a relatively small percentage, some FAA Airman Medical Certificate holders may be less sensitive to color than others depending on the color vision test the individual underwent during their medical examination (Rodriguez-Carmona et al., 2012).

Color Discrimination at Altitude

General aviation pilots may fly in unpressurized aircraft at altitudes above 10,000 feet (3048 meters). At higher altitudes there is less oxygen available and hypoxic conditions can arise. Leid and Campagne (2001) conducted a study in which participant color discrimination was tested at various altitudes (between 5,200 and 7,000 meters) during a mountain climbing expedition with trained mountain climbers. Most participants retained normal color vision at altitude despite a decrease in oxygen and physical exertion. Very few participants showed a slight deficiency in color perception in the blue-yellow axis. Leid and Campagne (2001) concluded that with the testing methods used, "severe hypoxia due to very high altitude and exacerbated by physical effort does not lead to major disturbances of colour perception" (p. S283).

Karakucuk, Oner, Goktas, Siki, and Kose (2004) conducted a study in which participant color discrimination was tested at two altitudes (1,060 and 3,000 meters). Unlike Leid and Campagne (2001), Karakucuk et al. (2004) used high school students as participants (with an average age of 15.06 years) and carried them to a 3000-meter mountain plateau via a bus. Karakucuk et al. (2004) reported that there was "a statistically significant deterioration in the blue-yellow range at 3000 m when compared with 1060 m" (p. 365). Deficiencies in the blue-yellow range at altitude were common in both Leid and Campagne's (2001) and Karakucuk et al.'s (2004) studies.

Laser Eye Protection

Kuyk et al. (2010) explain that "LEP are effectively spectral filters that block segments of the visible spectrum" (p. 1430). Blocking a particular color of light is an effective method to protect eyes against lasers of that color, however, spectral filtering results in altered color appearance dependent on the selected wavelengths (Kuyk et al., 2010). Harasaki and Kamiya (2005) in their study on LEP visors noted that:

> "an LEP visor completely changes the tint of the scene, because it sometimes cuts specific colors (spectrum) in the visible spectrum range. For example, if a pilot wears a LEP visor designed to cut red and green lasers, he/she might feel rather like a person who is red-green colorblind.

All red and green colors in the scene are blocked by the LEP visor in this case" (p. 3).

Kuyk, Garcia, Brockmeier, Gorsche, and Martinsen (2006) conducted a study in which 12 participants viewed colors through various filters that blocked light in different areas of the visible spectrum. Most of these participants were not able to correctly identify or name many of the hues presented when using the filters. It was also determined that not all filters affected color discrimination to the same extent (Kuyk et al., 2006).

To block laser light, LEP producers use technologically advanced dyes and dielectric coatings to either absorb or reflect laser light (Nakagawara et al., 2006). The difficulty for LEP producers is finding the balance between blocking enough laser-light to reduce glare, flash blindness, and distraction, and still allowing pilots to retain adequate color vision (Dykes et al., 2000). As time progresses, technology continues to improve and advancements in holography and optics technologies bring LEP producers closer to finding a suitable and effective solution (Nakagawara et al., 2006).

Dykes et al. (2000) found that when an LEP is designed to block a specific color, computer screens (narrow-band light) can be more susceptible to color appearance changes in that specific color than printed or real-life color (broad-band light). This is of particular concern to aviators because there is a growing use of screens in the cockpits of complex aircraft; newer aircraft are generally equipped with glass cockpits equipped with Primary Flight Displays (PFDs) and Multi-function Displays (MFDs).

LaFrance, Williamson, Svec, and Kuyk (2013) conducted a study to investigate the effects of different types of LEP on both “broad-band and narrow-band hue discrimination tasks” using “isoluminant caps” as the “broad-band illuminant” and an MFD as the “narrow-band illuminant”. This study, however, contrary to Dykes et al. (2000), found that the color-balanced LEP affected color discrimination for broad-band light sources more so than for narrow-band light sources (LaFrance et al., 2013). The researchers explain that this may have been due to the color-balancing of the lenses resulting in an “alignment between LEP transmission bands” and the visual output of the MFD (LaFrance et al., 2013). This finding can be useful in manufacturing LEP if the device is to be tailored to suit increased PFD and MFD usage (LaFrance et al., 2013).

Dykes et al. (2000) suggest that utilizing computer modeling for color appearance testing can help LEP designers and manufacturers to produce devices that are effective and usable. Lucassen and Toet (2006) developed a computer software program, TNO VisorSimulator, which can simulate the color perception changes that various LEP devices would effect. The software allows for testing of a multitude of spectral blocking filters in various regions of the visible spectrum, however, Lucassen and Toet (2006) warn that even though the simulator can display the effects of different filters on color appearance, producing filters with some spectral blocking combinations may not actually be possible. Kuyk et al. (2010) also conducted research into developing a computer-based tool that simulates color appearance when looking through LEP devices. The researchers developed a tool based on two software packages, SolidWorks™ and OptisWorks™, and concluded that, with this tool, color appearance through an LEP could be readily simulated with great precision, accuracy, and reliability (Kuyk et al., 2010).

Palakkamanil and Fielden (2015) discussed the possibility of negative effects when using LEP, other than color appearance, and concluded that "these issues must be eliminated or minimized so as not to hinder visual performance" (p. 432). These negative effects, which may result from the use of lens filters and dyes, include haze, distortions, aberration, and artifacts (Nakagawara et al., 2006; Palakkamanil & Fielden, 2015). In addition to retaining relatively accurate color vision, pilots must also have good visual acuity to be able to correctly discern objects and features at various distances (Harasaki & Kamiya, 2005). Pilots sometimes have to navigate using outside references and landmarks to determine location. Any LEP used should not hinder navigation or obscure objects in the distance.

Harasaki and Kamiya (2005) and Kuyk et al. (2010) explain that there is a growing use of lasers in military operations, and so development of LEP was necessary to ensure the safety of military personnel. Military LEP is required to meet military standards "such as withstanding shrapnel impact, ejection windblast, extreme temperature, and high altitude solar radiation" and must be compatible with other systems and gear used by military personnel (Harasaki & Kamiya, 2005, p. 1). These strict standards and requirements put a limit on what can be used for military LEP technologies (Harasaki & Kamiya, 2005).

Harasaki and Kamiya (2005) and the Japan Defense Agency were challenged with "developing LEP visors that both meet stringent military standards and are tough, easy to handle, and convenient to use" (p. 1). In their study, the authors presented their design concept and the results of testing done on the LEP visor prototype. The visor they produced was a polycarbonate with selected dyes designed to be incorporated into the helmets of the Japan Air Self-Defense Force. The dyes were selected based on results from a "chromatic performance simulation" conducted to ensure that the visor met the military optical requirements (Harasaki & Kamiya, 2005, p. 3). After the prototype was created, it was tested to ensure it also met the military ballistic and protection requirements.

One concern about a LEP device is its reaction to ultraviolet (UV) radiation. Harasaki and Kamiya (2005) explain that "dye breaching" can occur when LEP is exposed to UV radiation, which can decrease the LEP's ability to block laser light (p. 5). Sunlight contains UV radiation and so LEP devices worn by pilots, especially during high altitude flight, would be exposed to high amounts of UV radiation which can result in the degradation of its laser blocking abilities. In their UV radiation testing of the LEP visor, Harasaki and Kamiya (2005) surprisingly found that laser light blocking capabilities increased as the accumulated exposure to UV radiation increased; however, this was due to cracks developing in the visor after UV exposure which reduced the total light transmission and also reduced overall visibility. The authors concluded that LEP visors would have a lifespan and will need to be replaced periodically to ensure proper protection (Harasaki & Kamiya, 2005).

While military LEP must meet military compatibility and combat standards, LEP designed for civilian usage has fewer restrictions. LEP for industrial usage should meet the standards set out by the American Society of Safety Engineers in ANSI Z87.1-2003 (ANSI Z87.1-2003, 2003). According to the FAA, even if LEP technology was effective, integrating LEP into civil aviation would still be a challenge (Nakagawara et al., 2006). Issues such as headset and avionics compatibility, prescription lens compatibility, and pilot opinion and comfort may hinder pilots from investing in LEP or wearing it if provided (Nakagawara et al., 2006). If pilots wore effective LEP during arrival and departure phases of flight, it could mitigate the severity of a cockpit laser illumination and enhance safety during these critical phases of flight.

Conclusion

This chapter addressed some of the trends, issues, and obstacles that surround laser illumination incidents and LEP. Two different theories of color vision mechanisms were also highlighted. These theories may provide LEP researchers and developers with a framework to base designs upon. By conducting further research and analyses in this field, perhaps improved methods for laser illumination mitigation may emerge. In addition to protection devices, regulations, and regulation enforcement, awareness is a key player. Making pilots and the general public aware of the dangers and ramifications of aviation laser illuminations can help mitigate the risk and increase safety (Nakagawara et al., 2011a; FAA Order 2150.3B, 2016a).

Chapter 3
Methodology

Introduction

This chapter discusses the methodology that was employed while conducting this study and will provide descriptions of the methods used to obtain participants for the study, treatment of participants, the instruments and materials used, and the testing used for data collection. A brief description of the power analysis is also included. Additionally, this chapter reviews the analytical and statistical procedures used in the study.

Research Design

The purpose of this study was to investigate the effects of LEP on color recognition and discrimination. To investigate this matter, this quantitative research study was devised utilizing an exploratory modified quasi-experimental design. Three different types of eyewear were used in the study; two different LEP devices and one pair of clear protection eyewear. The first LEP, LEP1-RG, according to the manufacturer, comprised of bronze colored lenses and protects against red and green (RG) lasers. The second LEP, LEP2-RGB, comprised of green colored lenses and protects against red, green, and blue (RGB) lasers. The pair of clear protection eyewear (EP3-Clear) was used as a reference to which the effects of the LEP devices were compared. Participants underwent the Color-block test in order to determine the effects of the LEP on color recognition and discrimination. For statistical analysis of the data collected, Chi-squared tests were used.

Population and Sample

Population. The target population for this study is relatively large and consists of both male and female adults with normal color vision. The accessible population for this study was university students, faculty, and staff based at FIT who are over the age of 18 years with normal color vision. According to FIT's Fall 2016 Official University Enrollment Count, there are approximately 9,225 enrolled students at FIT which includes main campus, satellite campus, and online students (FIT, 2016). Of the 9,225 enrolled, 5,028 are enrolled at the main campus (FIT, 2016). While main campus, online, and satellite campus students are permitted to participate in the study, recruited participants are required to be physically present at FIT's main campus in Melbourne, Florida for the testing.

Sample. The sample for the study was selected from the accessible population using the convenience sampling method. Participants were recruited through email and word of mouth. Even though this research was aimed toward aviation professionals, this study did not require participants to have aviation skills or knowledge, and so students with normal color vision from any department, college, or program within FIT were eligible to be participants. The sample consisted of $N = 90$ participants who volunteered to be a part of the study. Participants' responses were kept anonymous and confidential.

Power Analysis

A power analysis was conducted a priori to determine the sample size for the study. This was done to ensure that a sufficient number of participants would be recruited to allow the study to have adequate statistical power. G*Power 3.1.9.2 was used to conduct the power analysis using the traditional values of .05 and 0.8 for α and power respectively, and 0.4 for a medium to large effect size. For the statistical test used in this study, Chi-square test, a value of 0.3 is considered a medium effect size, and a value of 0.5 is considered a large effect size (Gravetter & Wallnau, 2013). According to Gravetter and Wallnau (2013), effect size "is intended to provide a measurement of the absolute magnitude of a treatment effect" (p. 262). Prior studies in the color vision and color discrimination fields which found significant results utilized medium to large effect sizes and so a value of 0.4 was deemed appropriate for this study (Melamud, Simpson, & Traboulsi, 2006; Karakucuk et al., 2004). From the power analysis, the minimum sample size for this study was 86 participants. Therefore, it was ensured that over 86 participants were used in this study. Ninety (*N* = 90) participants were recruited for the study, with 30 participants in each of the three groups.

Study Instruments and Materials

Instruments

The data collection instruments that were used in this study were a questionnaire and the Color-block test. The questionnaire was used to collect demographic data on participants including participants' age, aviation background data, and color vision history. The Color-block test examined participant ability to recognize a color and discriminate between colors when using the LEP.

Questionnaires allow a relatively large amount of data to be collected in a short space of time, thus it was considered to be a good instrument for collection of demographic data. This data was stored and matched with the participant's Color-block test, allowing for the identification of trends in the data. Attention was given to the questionnaire's face and content validity through a review done by a human factors expert who has experience with human factors engineering research. Face validity helps to ensure that the participants accept the questionnaire, and content validity ensures that the questionnaire actually collects the data from participants that it was intended to collect (Ary, Jacobs, & Sorensen, 2010). There was no control over the participants' responses but the assumption was that participants were honest when responding.

To reduce the risk of including participants that do not have normal color vision, a ten-plate Ishihara test was conducted prior to data collection. This test assessed the participant's color vision and highlighted an individual with a red-green color vision deficiency, which is the most common color vision deficiency. The Ishihara test consisted of ten Ishihara plates each presented on a PowerPoint slide. The Ishihara plates contain seemingly random circles of different colors and sizes that form a number. An individual with normal color vision will see a particular number, but an individual with a red-green color vision deficiency will see a different number or no number at all. For example, in Figure 1, an individual with normal color vision will see the number 74, while an individual with a color vision deficiency may see the number 21 or no number at all (Ishihara, 1972).

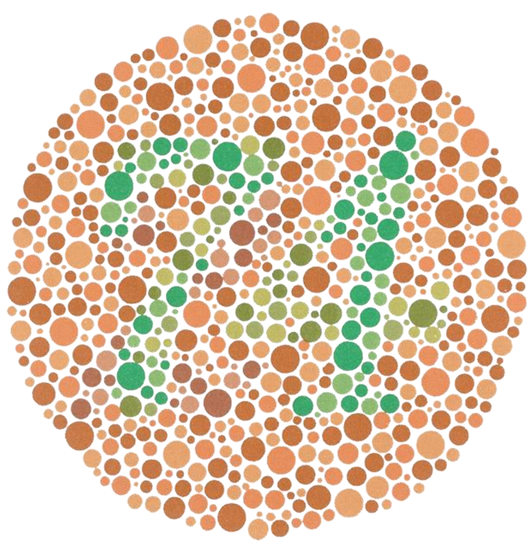

***Figure 1*: Ishihara Plate Sample**

To facilitate experience, participants were given a pre-test presentation of approximately five minutes, in which they were exposed to the color-blocks one at a time in a controlled manner. Each color-block/screen in the pre-test was shown for 20 seconds each. The timing for both the pre-test and the Color-block test were determined by conducting a pilot study prior to final data collection.

The Color-block test was used as an instrument to test participant color recognition and discrimination when using the LEP. The Color-block test consisted of a controlled PowerPoint presentation showing instructions and blocks (rectangles) of different colors (color-blocks). During the Color-block test, the participants first viewed a singular color without any eyewear for 10 seconds. The participant was then instructed by the test to put the eyewear on. After donning the eyewear, the participant was presented with a screen showing 12 different color-blocks and was required to choose the singular color-block viewed prior.

Materials

The materials used in this study include two LEP devices, one pair of clear protection eyewear and a laptop computer. The laptop screen display was calibrated to the manufacturer recommended (or highest) resolution and color settings. LEP1-RG had a visible light transmission of 18% and transmitted less than 10% of red light (630 – 670 nm wavelengths) and less than 4% of green light (532 nm wavelength). LEP1-RG complied with ANSI Z136.1 (American standard for safe use of lasers) and ANSI Z80.3 (American standard for sunglasses), and met the standards of ANSI Z87.1 (American standard for Occupational Personal Eye and Face Protection Devices). LEP2-RGB had a visible light transmission of 23.3% and transmitted approximately 6.3% of red light (633 – 640 nm wavelengths), approximately 3.2% of green light (532 nm wavelength), and approximately 3.2% of blue light (445 – 450 nm wavelengths). LEP2-RGB complied with ANSI Z136.1 and met the standards of ANSI Z87.1. The clear protection eyewear had no laser blocking capabilities and exceeded the standards of ANSI Z87.1. This study included the use of clear protection eyewear for comparison purposes.

Procedures

Before conducting the study, an application was sent to and approved by FIT's Institutional Review Board (IRB) to ensure that the necessary steps were taken to protect the participants of the study. This study posed no more risk to human health than wearing non-prescription spectacles and using a computer.

Prior to the beginning of the study, the participants were informed that the study would not exceed 25 minutes in length. Participants also received an affirmation by the researcher, through an informed consent document, that no identifying information would be released in the report of the study and all identifying information will be kept confidential. Each participant was given the opportunity to enter into a raffle drawing for a $25 gift card. To take advantage of this incentive, participants were given the option to identify themselves via an e-mail address and/or phone number. No identifying information was associated with data collection and identifying information given was not kept after the raffle drawing. Each participant also had the option to complete the study without being entered into the incentive raffle if so desired.

This study was exploratory in nature. One independent variable was the type of LEP (LEP1-RG, LEP2-RGB, and EP3-Clear). The other independent variable was color. Groups were distinguished by the type of LEP used. There were three groups: Group 1, LEP1-RG; Group 2, LEP2-RGB; Group 3, EP3-Clear (see Table 1). Participants were evenly distributed and randomly assigned to a group by the roll of a dice. Two numbers on the dice were assigned to each group. The group that corresponded with the number obtained on the dice roll was the group to which the participant was assigned.

Table 1
Group Number Allocations

Eyewear	**LEP1-RG**	**LEP2-RGB**	**EP3-Clear**
Group	1	2	3
Dice number assigned to group	1, 4	2, 5	3, 6

There was only one participant in the room per run along with the researcher. The questionnaire was administered first. Participants were placed into one of the three groups dependent on the number rolled on a dice. To complete each group with the necessary number of participants, if a participant rolled a number for a group for which data collection was already completed, the participant was asked to roll the dice again until a number of an incomplete group was achieved. During data collection this group completion technique was only used with the last two participants.

The laptop screen was calibrated using its control panel settings. The laptop was also physically set up at a distance of 40 cm from the edge of the table with a screen inclination angle of approximately 105° to allow for consistency among participants. These measurements were based upon the findings of Gangele and Mishra (2015) in their study "Optimal laptop VDU parameter setting using Taguchi method."

To assess participant color vision, participants underwent a ten-plate Ishihara test. Participants indicated to the researcher what number was observed in each of the Ishihara plates presented. Participants that correctly identified all the numbers presented in the Ishihara plates were considered to have normal color vision and were eligible to participate in the study. If a participant could not identify all of the presented numbers, that individual was informed that they do not meet the requirements of the study. An individual who was found to be ineligible for the study was still given the opportunity to enter into the incentive raffle.

All eligible participants then gained "experience" with the LEP by completing the pre-test presentation. The pre-test presentation was a controlled PowerPoint presentation that required participants to view various colors with and without the LEP prior to the Color-block test. Participants were allowed to freely don and remove the LEP during the pre-test presentation. Participants were presented with 12 singular color-blocks on a black background, one at a time, for 20 seconds each (see Figure 2). The optimal length of time that the color will be presented to the participant for this study was obtained during pilot testing.

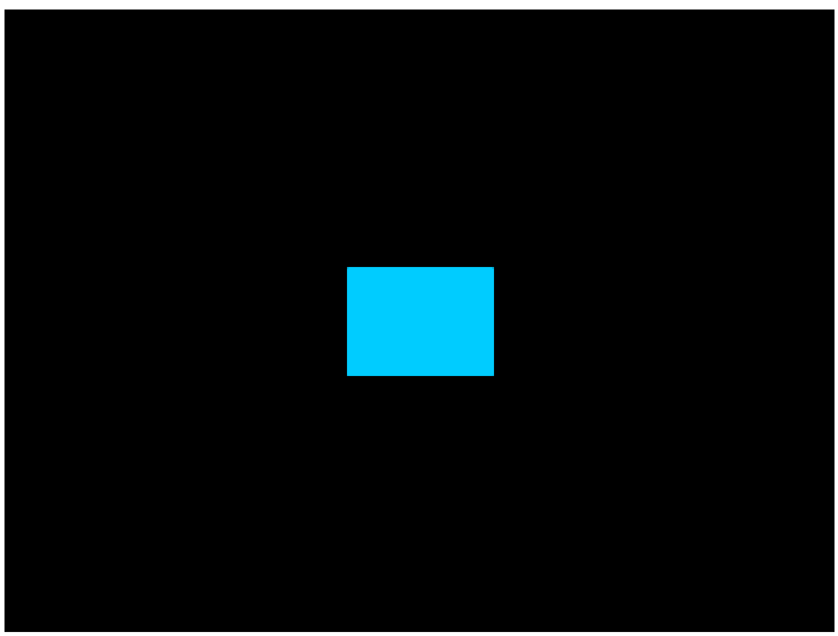

***Figure 2*: Example of Pre-test Presentation Display of Singular Color-Block**

Following the presentation of the singular blocks, participants were then presented with a screen showing all 12 of the color-blocks. This screen was viewed for 30 seconds (see Figure 3). This allowed participants to see the effects that the LEP had on different colors' appearances. These were the same color-blocks used in the Color-block test, except that they were presented in a different order and layout. The total experience time was approximately five minutes in length. The assumption was that during the pre-test presentation participants actually paid attention and gained experience viewing colors through the LEP.

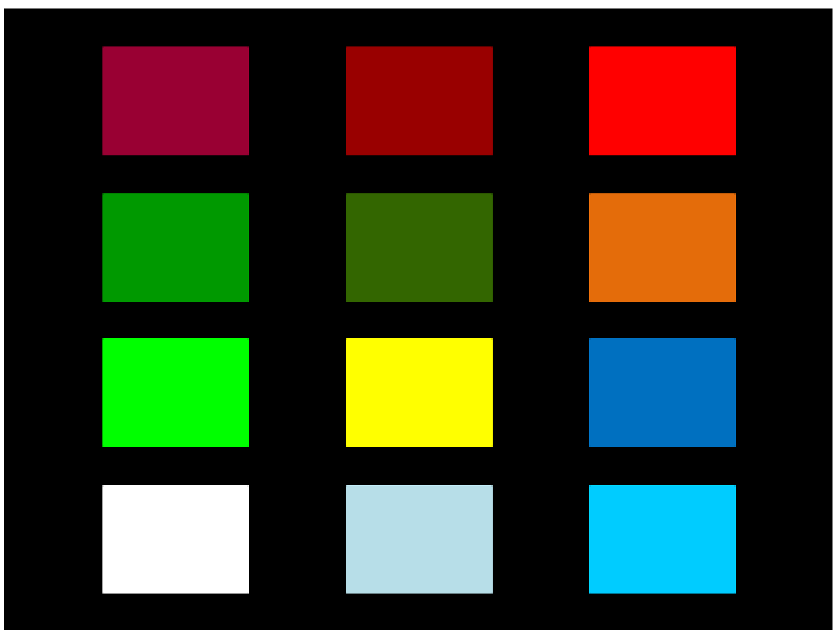

***Figure 3*: Example of Pre-test Presentation Display of All Color-Blocks**

The Color-block test consisted of a controlled PowerPoint presentation showing instructions on donning ad removing the eyewear, and blocks (rectangles) of different colors displayed on a black background. The black background was chosen based on previous similar color recognition and discrimination studies (Kuyk et al., 2010; LaFrance et al., 2013). The participant was first instructed to remove the eyewear and viewed a singular color-block (for example, Color b) without the eyewear (see Figure 4). Each participant had 10 seconds to view the color without the eyewear. The participant was then instructed to put on the eyewear, and was presented with a screen displaying 12 numbered color-blocks (see Figure 5). From the 12 color-blocks, the participant selected the color, by means of the number, that most resembled the previous color (Color b) that was viewed without the eyewear. The researcher noted which color-block the participant identified. This process was repeated for a total of four times with different colors (blue, green, amber, and red).

The number of colors and color-blocks that were correctly identified (out of the four) by each participant was recorded and associated with the appropriate participant's questionnaire. The data collected was used in statistical analyses to identify trends and relationships in the data and to make comparisons.

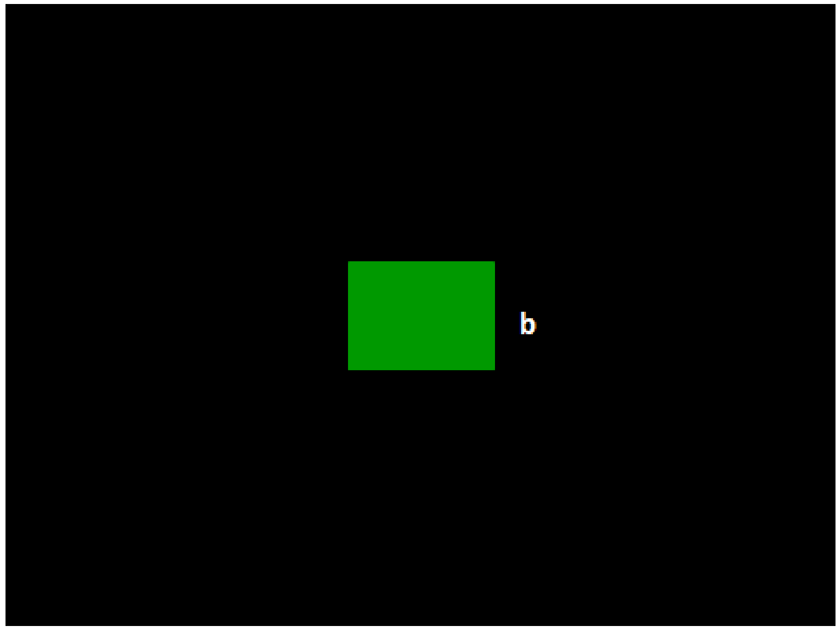

***Figure 4*: Example of Color-block Test Display of Singular Color-Block**

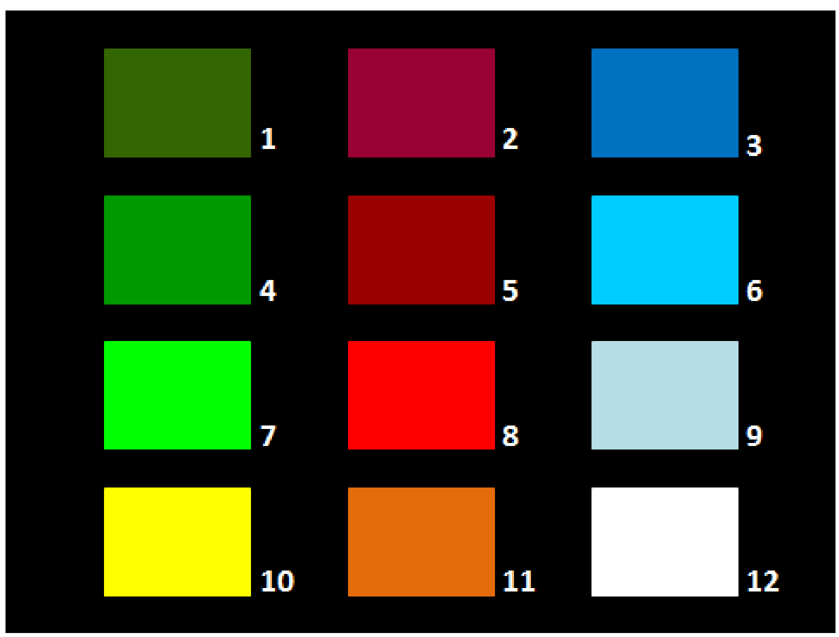

***Figure 5*: Example of Color-block Presentation Display of All Color-Blocks**

Variables

Independent variable

The independent variables in this study were the type of LEP and color. There was three different types of eyewear used in the study; two different LEP devices with different laser blocking capabilities, and one pair of clear protection eyewear with no special laser blocking capabilities. There were three participant groups based on the three types of eyewear. A description of the eyewear is given in the Materials section of this Chapter.

The other independent variable was color. Color recognition and color discrimination of four colors were examined in this study. These colors were: red, green, blue, and amber.

Dependent variable

The aim of this study was to investigate the effects that different LEP have on color recognition and discrimination abilities. To measure this, the dependent variables of this study are color recognition and color discrimination as measured by the number of correct color and color-block identifications on the Color-block test (out of the four colors presented). This measure of color recognition and discrimination is similar to that used in other studies; however, some other studies recorded the number of incorrect color identifications (Karakucuk et al., 2004;

LaFrance et al., 2013; Melamud et al., 2006). This was probably due to the types of testing which required participants to place hundreds of color-blocks, and in some cases over a thousand, in a particular order. For this study, recording the number of correct identifications sufficed since there are only four iterations.

Data Analysis

Descriptive statistics were used to report the percentages of participants in each age group and other demographic categories, and participant accuracy in the Color-block tests.

The null and alternative hypotheses for this study are as follows:

H_{01}: Laser eye protection has no significant effect on color recognition.

H_{A1}: Laser eye protection has a significant effect on color recognition.

H_{02}: Laser eye protection has no significant effect on color discrimination.

H_{A2}: Laser eye protection has a significant effect on color discrimination.

H_{03}: The laser eye protection's effect on color recognition and/or discrimination is the same for all colors.

H_{A3}: The laser eye protection's effect on color recognition and/or discrimination for at least one color is significantly different.

To test the study's hypotheses, Chi-squared tests were used. Two primary contingency tables were developed from the data collected. This statistical test was chosen due to the non-parametric nature of the data collected and was appropriate for statistical analysis when simultaneously comparing categorical variables. The traditional values of .05 and 0.8 were used for α and power respectively. All data analyses were conducted using statistical analysis software JMP and SPSS. Details on the data analyses are presented and further discussed in Chapters 4 and 5.

Participant Protection

Every effort was made to treat participants fairly and equally. Participation in the study was voluntary, and participants were not forced, pressured, or excessively coerced to complete the study. The participant was allowed to end the data collection at any time had the participant not wished to continue the study. The only identifying information that was collected were names and e-mail addresses of those participants who wished to be entered into the incentive raffle; however, no identifying information was associated with data collected in the questionnaires or Color-block tests. All of the data collected during the study will be kept securely in the College of Aeronautics at FIT. All participants were informed of this information prior to beginning the study.

Budget and Time Schedule

The research was conducted over four months which includes IRB submission and approval, participant recruitment, data collection and analysis. The research budget was approximately $60. This includes the cost of shipping the

LEP back to the manufacturers, obtaining the clear protection eyewear, and purchasing of the $25 gift card incentive for the participant raffle.

Summary

This study was designed to collect data on the effects of LEP on color recognition and discrimination of four colors. The methodology employed and the statistical analyses used are thought to be logical and appropriate for investigating the selected topic.

Chapter 4
Analysis

Introduction

This Chapter covers the analysis of the data collected using the methodology as described in Chapter 3, which employed a modified quasi-experimental design for data collection and used a Chi-square test for data analysis. The Chi-square test was used as the primary method to determine the statistical significance of the results, and post hoc tests were also conducted for further insight into significant results. The descriptive statistics of the sample will be discussed as well as the results from the Chi-square analysis. The descriptive statistics allow one to view the demographic characteristics of the sample used in the study. This can help determine the sample's similarity to the population and generalizability of the results.

As stated in Chapter 1, the research questions driving this study, along with their respective hypotheses are as follows:

Research Question 1. What is the effect of laser eye protection on color recognition?

- H_{01}: Laser eye protection has no significant effect on color recognition.
- H_{A1}: Laser eye protection has a significant effect on color recognition.

Research Question 2. What is the effect of laser eye protection on color discrimination?

- H_{02}: Laser eye protection has no significant effect on color discrimination.
- H_{A2}: Laser eye protection has a significant effect on color discrimination.

Research Question 3. Which color from those investigated is most greatly affected by laser eye protection?

- H_{03}: The laser eye protection's effects on color recognition and discrimination will be the same for all colors.
- H_{A3}: Color recognition or discrimination of at least one color will be significantly more affected by the laser eye protection.

Descriptive Statistics

This research used a sample size of 90 participants ($N = 90$). The data collected from each participant were considered to be complete so no data were excluded from the study. The data were input into statistical analysis tools, SPSS and JMP Pro, to identify the demographic characteristics and descriptive statistics of the sample. Of the 90 participants, 43 (48%) were male and 47 (52%) were female. Three age groups were represented in the sample; 18 – 29 years, 30 – 39 years, and 40 – 49 years. The great majority of participants (91%) fell into the first age group, 18 – 29 years (n = 82). The other two age groups, 30 – 39 (n = 6) and 40 – 49 years (n = 2) were represented by 7% and 2% of the sample. Several ethnicities were represented in the sample. Forty four (49%) participants identified as "Caucasian/White." This was the most represented ethnicity in the sample. The second most represented ethnicity was "Asian" with 14 (16%) participants. The other ethnicity categories, "Black/African American," "Hispanic/Latino," "Mixed," and "Other," were represented by 13 (14%), 11 (12%), 7 (8%), and 1 (1%) participants respectively. The most represented eye color was brown, with 67% of participants having brown eyes. Ninety-seven percent of participants were students at Florida Institute of Technology, with the remaining 3% being faculty and staff members. Table 2 provides further insight into the demographic composition of the sample.

The 90 participants were randomly separated into three groups of 30 participants through the use of dice rolls. Group 1 (LEP1-RG) consisted of 17 male (57%) and 13 female (43%) participants, and 90% of the group fell into the 18 – 29 years age group. Group 2 (LEP2-RGB) consisted of 11 male (37%) and 19 female (63%) participants, and 93% of the group fell into the 18 – 29 years age group. Group 3 (EP3-Clear) consisted of 15 male (50%) and 15 female (50%) participants, and 90% of the group fell into the 18 – 29 years age group.

Table 2
Demographic data of the sample

Variable		Number	Percentage of Total
Gender			
	Female	47	52.22%
	Male	43	47.78%
Age Group			
	1 (18 - 29)	82	91.11%
	2 (30 - 39)	6	6.67%
	3 (40 - 49)	2	2.22%
Race/ Ethnicity			
	Caucasian/White	44	48.89%
	Asian	14	15.56%
	Black/African American	13	14.44%
	Hispanic/Latino	11	12.22%
	Mixed Race	7	7.78%
	Other	1	1.11%
Eye Color			
	Brown	60	66.67%
	Blue	16	17.78%
	Green	8	8.89%
	Hazel	4	4.44%
	Other	2	2.22%
Major/Subject Area			
	Engineering	35	38.89%
	Aeronautics	32	35.56%
	Science	12	13.33%
	Business	4	4.44%
	Psychology	4	4.44%
	Education	3	3.33%

Inferential Statistics

The purpose of this study was to investigate the effects of LEP on color recognition and color discrimination using two different LEP apparatus, and a pair of clear protection eyewear. In order to answer the research questions the data were analyzed and trends identified. This study examines the relationship between only categorical variables as the independent variables, LEP and color, and the dependent variables, color recognition and color discrimination are all categorical. A Chi-square test of the contingency tables was used to analyze the data and the significance of the differences among the groups. The Chi-square test was the most appropriate for the data collected because of the non-parametric nature of the data, and because it supports the analysis of relationships between categorical variables and determines whether differences among groups are significant or possibly due to chance. It was confirmed that the data met the assumptions of the Chi-squared analysis. These assumptions include that the expected frequency in any cell of the contingency table was not less than five, and that the observations were independent of each other (Ary, Jacobs, & Sorensen, 2010). In addition to the Chi-square test, post hoc analyses were conducted with the variables found significant.

Chi-Square Analyses

The data collected were put into two contingency tables for Chi-square tests; one table for color recognition and one table for color discrimination (see

Table 3 and Table 4). These tables seek to compare two categorical variables; the eyewear and the colors. The data entered into the tables are the frequencies of correct color identifications with the specific row and column condition.

Table 3
Color Recognition: Number of correct color identifications

	LEP1-RG	LEP2-RGB	EP3-Clear
Blue	30	24	30
Green	30	25	30
Amber	10	15	30
Red	28	29	30

Table 4
Color Discrimination: Number of correct color-block identifications

	LEP1-RG	LEP2-RGB	EP3-Clear
Blue	26	13	30
Green	16	22	30
Amber	8	13	30
Red	19	27	30

The results of the two primary Chi-square tests are discussed in the following sections.

Color Recognition. This Chi-square test compared the type of eyewear and the number of correct color identifications. When analyzing the LEP's effects on color recognition the result was not statistically significant, χ^2 (6, N = 311) = 8.93, p

= .17. This suggests that there is no significant difference in participant color recognition when using the different eyewear and identifying different colors/hues. The majority of participants were able to correctly identify different colors regardless of the eyewear used. Ninety-three percent of participants (n = 84) were able to identify blue, 94% (n = 85) were able to identify green, 97% (n = 87) were able to identify red, however, only 61% (n = 55) were able to identify amber.

Color Discrimination. The results of the Chi-square analysis for color discrimination suggest that the overall effect of LEP on color discrimination was just statistically significant, χ^2 (6, N = 264) = 12.66, p = .05. When using the LEP the majority of participants were able to identify or recognize the correct color, but color discrimination between different shades of the same general color proved to be less accurate. Seventy-seven percent of participants (n = 69) were able to identify the correct blue color-block, 76% (n = 68) were able to identify the correct green color-block, 84% (n = 76) were able to identify the correct red color-block, but only 57% (n = 51) were able to identify the correct amber color-block.

Post hoc Chi-square analyses suggest that there were statistically significant differences between the effects of the different types of eyewear, χ^2 (2, N = 264) = 17.66, p < .01. Further analyses, pairwise comparisons, revealed that there were statistically significant differences between Group 1 (LEP1-RG) and Group 3 (EP3-Clear), χ^2 (1, N = 189) = 13.76, p < .01, and between Group 2 (LEP2-RGB) and Group 3 (EP3-Clear), χ^2 (1, N = 195) = 10.39, $p < .01$. The differences between Group 1 and Group 2 were not statistically significant, χ^2 (1, N = 144) = 0.25, $p = .62$.

Colors. The Chi-square test of goodness of fit suggests that the difference in color discrimination of each color was not statistically significant, χ^2 (3, N = 264) = 5.12, $p = .16$. This suggests that, statistically, the accuracy of color discrimination may be equal for different shades of the colors investigated. Despite the statistical insignificance of differences in the LEP's effects among the colors, the data collected suggest that participants had the most trouble identifying the amber color; 43% (*n* = 51) of all participants could not identify the amber color-block when using the LEP. Seventy three percent (*n* = 22) of participants in Group 1 (LEP1-RG) and 57% (*n* = 17) of participants in Group 2 (LEP2-RGB) could not identify the amber color-block correctly, whereas, all the participants (*n* = 30) in Group 3 (EP3-Clear) were able to identify the amber color-block correctly.

On the other hand, the statistical analysis, Chi-squared test of goodness of fit, suggests that the differences in color recognition of each color were statistically significant, χ^2 (3, N = 311) = 8.94, $p = .03$. This suggests that statistically, from those investigated, there is at least one color that is more or less affected by LEP than the others. Pairwise comparisons revealed that color recognition of amber when using LEP is significantly different from the other colors (see Table 5).

Table 5
Pairwise Comparisons of Color Recognition Accuracy

	Color pairs					
	Amber/ Blue	Amber/ Red	Amber/ Green	Blue/ Red	Blue/ Green	Green/ Red
χ^2	6.05	7.21	6.43	0.05	0.01	0.02
df	1	1	1	1	1	1
N	139	142	140	171	169	172
p	.014	.007	.011	.819	.939	.879

Decision on hypotheses

Research Question 1 asked "What is the effect of laser eye protection on color recognition?" Based on the results of the statistical analyses, the null hypothesis (H_{01}) which states that laser eye protection has no significant effect on color recognition, cannot be rejected; the research failed to reject the null hypothesis. In this study, LEP had no significant effect on color recognition.

Research Question 2 asked "What is the effect of laser eye protection on color discrimination?" Based on the results of the statistical analyses, the null hypothesis (H_{02}) which states that laser eye protection has no significant effect on color discrimination, can be rejected; the research rejects the null hypothesis and accepts the alternative hypothesis. In this study, LEP had significant effect on color discrimination. Thus, one can determine that using LEP can reduce the accuracy of one's color discrimination.

Research Question 3 asked “Which color from those investigated is most greatly affected by laser eye protection?” Based on the results of the statistical analyses, the null hypothesis (H_{03}) which states that the laser eye protection’s effects on color recognition and discrimination will be the same for all colors, can be rejected; the research rejects the null hypothesis and accepts the alternative hypothesis. The alternative hypothesis (H_{A3}) states that color recognition or discrimination of at least one color will be significantly more affected by the laser eye protection.

Summary

The analyses conducted provide evidence that the use of LEP can hinder color discrimination accuracy, more so than color recognition accuracy. Participants were able to recognize the colors, blue, green, amber, and red, relatively accurately but the results suggest that it was more difficult for participants to discriminate between different shades of each color. Amber proved to be the color that was least accurately recognized and least accurately identified when using LEP. There were also differences in the effects of the individual LEP devices on color discrimination when compared to the clear protection eyewear. This suggests that using LEP has the potential to affect color discrimination accuracy.

Summary of Hypothesis Testing

The purpose of this study was to determine the effects of LEP on color recognition and discrimination of a set of colors. There were three sets of hypotheses that were investigated. The research failed to reject null hypothesis 1, and so suggests that in this study LEP had no significant effect on color recognition. The research rejects null hypothesis 2 and accepts alternative hypothesis 2, which suggests that the LEP had a significant effect on color discrimination. The research also rejects null hypothesis 3 and accepts alternative hypothesis 3, which suggests that color recognition of at least one of the investigated colors was significantly more affected by the LEP.

Chapter 5
Conclusion

Overview

Aviation cockpit illuminations and laser strikes are on the rise and pose a threat to aviation safety and flight crew health. Laser cockpit illuminations have the potential to temporarily blind and distract pilots during critical phases of flight. Over half of the reported laser strike incidents occurred with commercial aircraft. This suggests that laser strikes not only put pilots in peril, but passengers as well. Pilots have the responsibility of getting their passengers to their destinations safely, and laser strikes can hamper the safety of the flight. Presently, there has not been a loss of life or substantial damage to property resulting from a laser strike. However, this is a growing problem with potential impact to the safety of flight crews, passengers, and the general public. It is important to be proactive from a safety perspective versus reactive in seeking to prevent an accident. In order to mitigate the potential hazards that aviation laser strikes pose, further measures should be taken, whether by law enforcement and regulators, or by air carriers and pilots themselves. LEP is one mitigation method currently available to pilots. LEP designed for pilots must allow them to retain accurate color recognition and discrimination abilities, because aviation utilizes colors to indicate different instructions, areas, and conditions.

The aim of this study was to investigate the effects of LEP on color recognition and discrimination using two types of LEP that are currently available, alongside a pair of clear protection eyewear with no laser blocking capabilities. This study examined the LEP's effects on four colors, blue, green, red, and amber. The study sought to answer the following three research questions:

1. What is the effect of laser eye protection on color recognition?
2. What is the effect of laser eye protection on color discrimination?
3. Which color from those investigated is most greatly affected by laser eye protection?

As noted in Chapter 4, this study used a sample size of 90 participants and Chi-square analyses were conducted to determine the statistical significance of results.

Summary of Research Findings

This study found that the LEP effects on color recognition were not statistically significant, χ^2 (6, N = 311) = 8.93, p = .17. The majority of participants were able to correctly identify different colors regardless of the eyewear used.

The study found that the LEP effects on color discrimination were marginally statistically significant, χ^2 (6, N = 264) = 12.66, p = .05. As explained in Chapter 4, most participants were able to identify or recognize the correct color when using the LEP, but fewer participants were able to identify the exact color-block. Post hoc pairwise comparisons, revealed that there were statistically significant differences between Group 1 (LEP1-RG) and Group 3 (EP3-Clear), χ^2 (1, N = 189) = 13.76, $p < .01$, and between Group 2 (LEP2-RGB) and Group 3 (EP3-Clear), χ^2 (1, N = 195) = 10.39, $p < .01$. The differences between Group 1 and Group 2 were not statistically significant, χ^2 (1, N = 144) = 0.25, $p = .62$.

The results suggest that, from the colors investigated, color recognition of amber was significantly different from the other colors. This finding suggests that amber was the most difficult color to identify when using the LEP. Pairwise comparisons revealed the statistically significant relationships between amber and blue, χ^2 (1, N = 139) = 6.05, $p = .01$, amber and red, χ^2 (1, N = 142) = 7.21, $p = .007$, and amber and green, χ^2 (1, N = 140) = 6.43, $p = .01$. The relationships between the other colors were not statistically significant.

Discussion and Interpretation of Findings

This study found that the LEP effects on color recognition were not statistically significant, χ^2 (6, N = 311) = 8.93, $p = .17$. This suggests that there was no significant difference in participant color recognition when using the different LEP. Color recognition is the ability to recognize or identify a color. For example, the participant identified that a blue color-block is blue, as opposed to green. It is the ability to tell the difference between colors of different families. Color recognition is extremely important when flying because several aspects of aviation rely on color coding, including navigation charts, aircraft instruments and lights, and airport lighting. This study found that the use of LEP did not have a significant effect on color recognition and this could mean that pilots using LEP can retain near accurate color recognition abilities.

The study found that the LEP's effects on color discrimination were marginally statistically significant, χ^2 (6, N = 264) = 12.66, $p = .05$. Color discrimination is the ability to identify differences between different colors and choose a specific color from a group of colors (for example, choosing a specific shade of red from a group of other colors, including other shades of red). As stated prior, most participants were able to identify or recognize the correct color when using the LEP, but fewer participants were able to identify the exact color-block. Thus, color discrimination between different shades of the same general color proved to be less accurate. Further analyses, the pairwise comparisons, revealed that there were statistically significant differences between Group 1 (LEP1-RG) and Group 3 (EP3-Clear), χ^2 (1, N = 189) = 13.76, $p < .01$, and between Group 2 (LEP2-RGB) and Group 3 (EP3-Clear), χ^2 (1, N = 195) = 10.39, $p < .01$. The differences between Group 1 and Group 2 were not statistically significant, χ^2 (1, N = 144) = 0.25, $p = .62$. These pairwise comparisons suggest that there were significant differences between color discrimination with and without LEP. Color discrimination was less accurate when using LEP, than when using clear protection eyewear. However, when examining color discrimination between the types of LEP, the differences were not significant. This suggests that neither of the two LEP used in the study were better for color discrimination than the other. Fortunately pilots are not usually faced with a situation in-flight in which they must discriminate between two colors in the same color family, especially not during critical phases of flight.

The results suggest that, from the colors investigated, amber was the most difficult color to identify when using the LEP. Some participants identified the amber color-block as red and the red color-block as amber with both LEP used in the study. There may be several reasons for this finding. This may be due to the fact that amber is a color between yellow and orange and not a pure color, whereas the other three colors, red, green, and blue, are pure primary colors of light.

General Discussion

The three groups were not perfectly matched with regards to gender and other demographics; however there were no significant trends observed with regards to demographics and color recognition and discrimination, and so the slightly different compositions of the groups should not have had a significant effect on results. The sample for this study did not provide enough variety in age groups to investigate trends with respect to age.

With respect to the first research question on what is the effect of laser eye protection on color recognition, participants in Group 1 (LEP1-RG) performed relatively well. All participants were able to correctly recognize blue and green, 93% of participants in the group were able to correctly identify red, and 33% of participants were able to correctly identify amber. LEP1-RG blocks red and green laser light and so this may explain the few participants that incorrectly identified red. The participants that were incorrect identified red as amber and amber as red. Color recognition in Group 2 (LEP2-RGB) was slightly different from Group 1. Ninety-seven percent of participants in the group were able to correctly identify red, however, 80% were able to correctly identify blue, 83% were able to identify correctly green, and 50% were able to correctly identify amber. LEP2-RGB blocks red, green, and blue laser light and so this may explain the differences seen, especially in the blue and green colors. The participants that were incorrect identified red as amber, amber as red, blue as green, and green as blue. With EP3-Clear (Group 3), the clear protection eyewear, 100% of participants were able to correctly identify and select all color-blocks. Based on the results of the statistical analyses, the null hypothesis (H_{01}) which states that laser eye protection has no significant effect on color recognition, cannot be rejected. In this study the color recognition differences among the groups were not enough to be considered significant.

With respect to the second research question on what is the effect of laser eye protection on color discrimination, the results for color discrimination were different from the color recognition results. Based on the results of the statistical analyses, the null hypothesis (H_{02}) can be rejected and thus, the alternative hypothesis (H_{A2}) which states that laser eye protection has a significant effect on color discrimination is accepted.

With LEP1-RG, which blocks red and green laser light, 87% of participants in the group were able to select the correct blue color-block, 53% were able to select the correct green color-block, 27% were able to select the correct amber color-block, and 63% were able to select the correct red color-block. The lower percentages in red and green can be explained by the design of the eyewear, which was to block red and green laser light. With LEP2-RGB, which blocks red, green, and blue laser light, 43% of participants in the group were able to select the correct blue color-block, 73% were able to select the correct green color-block, 43% were able to select the correct amber color-block, and 90% were able to select the correct red color-block. The lower percentages in blue and green can be explained by the design of the eyewear, which was to block red, green, and blue laser light. The data suggest that color discrimination of red was less affected by LEP2-RGB than by

LEP1-RG. This may be explained by the different designs of the LEP devices. LEP2-RGB was designed to allow approximately 6.3% of red light through the lenses, whereas LEP1-RG was designed to allow less than 10% of red light through. LEP1-RG also blocks a wider red spectral range (630 – 670 nm) than LEP2-RGB (633 – 640 nm).

With respect to the third research question on which color from those investigated is most greatly affected by laser eye protection, amber was the color that was least recognized and identified. Based on the results of the statistical analyses, the null hypothesis (H_{03}) can be rejected and thus the alternative hypothesis (H_{A3}) which states that color recognition or discrimination of at least one color will be significantly more affected by the laser eye protection is accepted. The colors used in the study were included due to their prevalent use in the aviation industry. One reason for this apparent greater effect on amber could have been that the other colors, red, green, and blue, each had three shades in the Color-block test that were obviously in the color family; however, amber was grouped with the yellow family. This grouping may have not been accurate since amber can be considered a color that is between yellow and orange. Amber was also the only color investigated that was not a primary color of light, and was not addressed by the LEP manufacturers.

The difference in the results for color recognition and color discrimination suggests that is was more difficult for participants to identify the exact color than it was to identify the family of the color. Overall, it seems as though the use of LEP may allow pilots to retain sufficient color recognition abilities. This suggests that LEP may be an effective and feasible laser strike mitigation method.

Uncontrolled Variables

One variable that could not be controlled in this study was memory. Memory played a small part in the Color-block test since it required participants to execute slightly delayed color matching in which they had to remember what color they first viewed without the LEP. This study attempted to view and mitigate the effects of memory by having the control group, EP3-Clear. Due to the fact that 100% of participants in the control group, EP3-Clear, identified the color-blocks correctly suggests that memory should not have posed a significant hurdle to participants in any of the groups, and that incorrect color-block selections were due to the effects of the LEP.

The effect of a color on the appearance of another was an uncontrolled variable in this study. Background and adjacent colors can have an effect on the appearance of a color (Todorovic, 2002). In this study there were four choice selection screens on which the color-blocks were arranged differently. These different arrangements may have introduced differences in the way the colors appeared due to the color-blocks' proximity to different colors. This study tried to mitigate this effect with even spacing and rearranging the colors within their color families. For example, the red shades were kept near together, while the blue shades were kept near together. A black background was also used for all screens to prevent the introduction of further uncertainty.

Another uncontrolled variable was a participant's prior experience with LEP. This study did not take into account a participant's prior experience with different types of LEP. Some participants, especially those in science and engineering fields, may have worked with standard laboratory LEP prior to this study, and so those participants may have been more familiar with the effects of LEP.

While the study attempted to test color vision to ensure that participants were not color blind, the test used, the Ishihara plates, does not test for every type of color vision deficiencies. The Ishihara plates address the most common types of severe color vision deficiency; however, there are several other types of less severe deficiencies that present themselves in different ways. The Ishihara plates may not detect all of these deficiencies and so it is possible that some participants may have had a color deficiency. Color vision deficiencies can alter an individual's ability to discriminate between different colors, and so would have affected the results of this study. With the time frame and resources for this study, it would not have been feasible to test for every color deficiency; however, color vision deficiencies are generally only present in a relatively small percentage (2% - 8%) of a population (Delpero et al., 2005).

Limitations and Delimitations

In this study, only two types of LEP were used. These may not be representative of every LEP device available to pilots. Some LEP devices block laser light via different methods and perhaps these would have different effects on color recognition and discrimination.

Another limitation of this study is that a convenience method of sampling was used to recruit participants from a relatively small part of the population. This may limit the population generalizability of the results. The entire sample was comprised of Florida Institute of Technology (FIT) students, faculty, and staff who volunteered to participate. The sample obtained was comprised of a high percentage of individuals between ages 18 – 29 years. This limitation was not unforeseen since data collection occurred on the university campus, however, this research made the use of the available resources.

Rearranging the colors on the choice selection screens of the Color-block test helped prevent participants from learning where each color would be; however, it may have introduced the issue of the effects of a color's proximity to other colors, which can alter the appearance of a color. As stated prior, this study tried to mitigate this effect with even spacing and rearranging the colors within their color families. Every participant, however, was presented with the same experience and same Color-block test presentation. This was done to limit introducing further uncertainty and other variables.

Defining "experience" as five minutes of LEP usage can be viewed as a delimitation in this study. Five minutes may or may not have been long enough for a participant to truly gain experience with the LEP. Perhaps with longer and more involved exposure to the LEP devices, participants would be able to better learn how the LEP affects color appearance. However, in order to successfully recruit a sufficient number of participants and keep participant attention, pilot testing suggested that the ideal time to dedicate to experience was five minutes.

As stated prior, memory played a small part in the Color-block test, however this study attempted to view and mitigate its effects. The control group, EP3-Clear, allowed the researcher to view any effects that memory had on the testing, however 100% of participants in that group identified the color-blocks correctly. This suggests that memory did not have a significant effect on participants in any of the groups, and that incorrect color-block selections were due to the effects of the LEP.

It is important to note that this study focused on civil aviation and the results may not be generalizable to military aviation LEP. Military aviation LEP may be required to meet strict military standards and must be compatible with other systems and gear used by military personnel inside and outside of the aircraft. These strict standards and requirements put a limit on what can be used for military LEP technologies (Harasaki & Kamiya, 2005). Civil aviation LEP is currently not highly regulated may not have to be as limited as military LEP.

Practical Implications

The results of this study suggest that LEP available on the market can allow users to retain sufficient color recognition. This would suggest that LEP, designed with pilots in mind, can be an effective way to mitigate the effects of a cockpit laser illumination and thus, increase safety. On the other hand, the results also suggest that LEP available on the market may not allow users to retain accurate color discrimination abilities. This would suggest that further improvements are required to obtain a more effective LEP that allows for better color discrimination. However, as stated in the previous section, pilots generally are not presented with many situations in-flight in which they must discriminate between two colors in the same color family or hue.

The results also suggest that currently available LEP may not allow for accurate color recognition of amber. When using LEP individuals may have a tendency to mistake amber for red. This would have to be something that users should keep in mind when wearing these types of LEP. Generally, with respect to airport and in-cockpit lighting, briefly mistaking amber for red is not a devastating issue. In the cockpit amber typically alerts pilots to an instrument, condition, or quantity that may need further attention. The color is used more with CAUTION events or lights, rather than with WARNING or DANGER alerts, which typically use red.

This study can bring awareness to the growing problem of aviation laser strikes and cockpit illuminations, and highlights a potential solution. Perhaps some of the violators do not know the ramifications of their actions when they point lasers at aircraft, and perhaps some pilots are unaware of the growing problem.

Recommendations for Future Research

The number of aviation laser strikes is unfortunately growing, and thus, mitigation methods should be developed and shared with the aviation industry. This section discusses research ideas that could be useful in the future for the aviation industry.

Increased number of study colors and LEP. This study only took four colors and two types of LEP into consideration. The smaller scale of this study may limit its generalizability. This study however, provides a starting point for future research. Future research endeavors can use a similar methodology but on a much larger scale, with a larger number of participants, colors and LEP, in order to further investigate the relationships. LEP using different methods of laser protection, such as dielectric coatings, can also be included in future research to make comparisons between the methods of blocking laser light. If participant color vision performance is significantly better with one particular mechanism of blocking laser light, further resources can be put into fine tuning that mechanism to build the best LEP for pilots.

Retractable visors for windshields of aircraft. Some LEP use advanced dyes to absorb and reflect laser light which affords their laser blocking abilities. Currently, permanent windshield LEP is not a viable option because “dye breaching” can occur when the LEP material is exposed to UV radiation (Harasaki & Kamiya, 2005, p. 5). Dye breaching decreases the laser protection’s ability to block laser light, rendering it ineffective (Harasaki & Kamiya, 2005). Sunlight contains UV radiation and so LEP devices placed directly on aircraft windshields would be exposed to high amounts of UV radiation, especially during high altitude flight, which can result in the degradation of its laser blocking abilities.

One idea to better incorporate LEP into the cockpit is through the use of a retractable visor in the aircraft. This could be a visor made of the spectral filters that comprise the LEP that would usually sit above the pilots, near the roof of the cockpit. The pilots would be able to extend or retract this visor when necessary, for example, when on approach into an airport notorious for laser strikes. The retraction or extension could manual or automated depending on the design of the aircraft. This, of course, is dependent on several conditions such as cost, different cockpit designs, and safety procedures. This idea may be worth further research to investigate its feasibility.

Color compensating instruments. Designing PFD and MFD technologies with the ability to change color characteristics such as hue, saturation, and warmth, could be useful to enhance pilot color recognition and discrimination when using LEP in the cockpit. There could be a setting that color-compensates for the use of different types of LEP. This type of setting should be easily selected and deselected. This type of color-compensating display is an area for further research to investigate its feasibility.

Standards for civil aviation LEP. The manufacturers of the LEP devices used in this study met, and exceeded, the American National Standard for occupational and educational personal eye and face protection devices (ANSI Z87.1-2003, 2003). While these standards are a very useful starting point, they do not specifically address some of the needs of aviation. Many aspects of aviation are duly regulated and LEP specifically for aviation should meet aviation standards and criteria. Military aviation LEP adheres to strict standards and civil aviation LEP should have standards of its own, whether modelled after military LEP or occupational LEP. Research into determining these types of standards could be useful for developing improved LEP devices.

Location of individuals who violate regulations. Due to the volatile nature of a laser strike incident, it is difficult for law enforcement to locate and apprehend individuals who point lasers at aircraft. Perhaps future research could be investigated to suggest an improved method of tracking and locating individuals who contribute to aviation laser strikes.

Summary

The purpose of this study was to investigate the effects of LEP on color recognition and discrimination. The findings suggest that there was no significant effect on color recognition, but a significant effect on color discrimination. The findings also suggest that color discrimination of amber was the most affected by the LEP. No significant trends with respect to demographics and color recognition and discrimination were found.

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Appendix A
Informed Consent

Informed Consent

Please read this consent document carefully before you decide to participate in this study. The researcher will answer any questions before you sign this form.

Study Title: The Effects of Laser Eye Protection on Color Recognition and Discrimination
Purpose of the Study: The aim of this study is to investigate the effects of laser eye protection (LEP) on color recognition and discrimination.

Procedures: The time required to complete participation in this study is approximately 20 minutes. You will first be required to fill out a short questionnaire. You will then be asked to view and compare a series of colors using a pair of non-prescription eyewear.

Potential Risks of Participating: Risks associated with this study are minimal and are no more than risks associated with everyday life.

Potential Benefits of Participating: This study brings awareness to the hazards associated with aviation laser strikes. The results may potentially show that laser eye protection can be an effective means to protect pilots from laser strikes.

Compensation: You will be offered the chance to enter into a raffle for a $25 gift card.

Confidentiality: Your identity will be kept confidential to the extent provided by law. Your information will be assigned a code number, instead of any personally identifying information. Any identifying information collected will not be associated with the data collected for the study. The list with participant names and/or contact information will be kept in a locked file in the College of Aeronautics. When the study is completed and the data has been analyzed, the list will be destroyed. Your name will not be used in any report.

Voluntary participation: Participation in this study is completely voluntary. There is no penalty for not participating. You may also refuse to answer any of the questions asked.

Right to withdraw from the study: You have the right to withdraw from the study at any time without consequence.

Whom to contact if you have questions about the study: Sherisse Pierre, pierres2011@my.fit.edu

Whom to contact about your rights as a research participant in the study:

Dr. Lisa Steelman, IRB Chairperson
150 West University Blvd.
Melbourne, FL 32901

Email: lsteelma@fit.edu Phone: 321.674.8104

Agreement:

- ☐ I am 18 years or older.
- ☐ I have read the procedure described above. I voluntarily agree to participate in the procedure and I have received a copy of this description.

Participant: ____ Date: ________________

Principal Investigator: ________________________________ Date: ________________

Appendix B
Questionnaire

LEP and Color Recognition and Discrimination Questionnaire

Thank you for participating in this study. Please respond to the following items honestly and to the best of your ability. If you have any questions please ask the researcher.

Gender

☐Male ☐Female ☐Other

Age

☐18 – 29 ☐30 – 39 ☐40 – 49 ☐50 – 59 ☐60 +

Race/Ethnicity (Select all that apply)

☐Hispanic/ Latino ☐Caucasian/White ☐Black/African/African American
☐Asian ☐Native American ☐Pacific Islander ☐Other:_______.

Eye color

☐Brown ☐Blue ☐Green ☐Hazel ☐Other: _______.

Major/Degree program area: ____.

Year

☐Freshman ☐Sophomore ☐Junior ☐Senior

☐Graduate ☐Faculty ☐Staff

Color vision history

Have you ever been tested for color-blindness? ☐Yes ☐No

Have you ever been told by a medical professional that you may be color-blind or have a color vision deficiency? ☐Yes ☐No

Aviation experience

☐None ☐Student Pilot certificate ☐Private Pilot Certificate

☐Commercial / ATP Pilot certificate ☐Other: _____________.

---------------------------------- Below to be filled out by researcher ----------------------------------

Dice roll number:

Participant wore spectacles during test? Yes No

Appendix C
Contingency Tables and Chi-square Results

Appendix C contains the contingency tables used for the Chi-square analyses to determine significant differences among groups with respect to the demographic data.

Table 6
Contingency Table for Gender and Color Discrimination Accuracy

	Blue	Green	Amber	Red
Male	33	31	23	34
Female	36	37	28	42

χ^2 (3, N = 264) = 0.16, p = .98

Table 7
Contingency Table for Eye Color and Color Discrimination Accuracy

	Blue	Green	Amber	Red
Blue	13	12	12	15
Brown	45	46	29	48
Other	11	10	10	13

χ^2 (6, N = 264) = 1.57, p = .95

Table 8
Contingency Table for Ethnicity and Color Discrimination Accuracy

	Blue	Green	Amber	Red
Asian	8	9	6	12
Black/ African American	10	7	4	9
Hispanic/ Latino	9	9	6	9
Caucasian /White	34	36	32	40
Other	8	7	3	6

χ^2 (12, N = 264) = 4.26, p = .98 *

*p value is an estimate since all cells do not meet the assumption of having a value of at least 5.

Table 9
Contingency Table for Subject Area and Color Discrimination Accuracy

	Blue	Green	Amber	Red
Aeronautics	23	23	11	26
Business/Edu/Psych	9	9	9	9
Engineering	28	27	22	30
Science	9	9	9	11

χ^2 (9, N = 264) = 3.42, p = .95