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Human Factors Evaluation of Commercial Aviation, Low Intensity, Iteration 2 (CALI-2) Laser Eye Protection

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16. Abstract

Laser strikes are an ever-increasing concern in the civil aviation community and are of particular concern to the Federal Aviation Administration (FAA). They pose a direct threat to aviation safety and air traffic coordination, particularly when they occur during critical phases of flight such as takeoff and landing. Laser strikes cause a variety of negative physiological and psychological effects, including glare, flash blindness, afterimages, and startle (Nakagawara et al., 2003, 2004). Laser eye protection (LEP) spectacles are designed to mitigate these effects by attenuating the visible and infrared light emitted by handheld lasers. While LEP spectacles are effective in mitigating the impacts of laser strikes on pilots, the attenuating properties of the lenses cause a shift in color perception. As such, wearing the LEP spectacles may impact pilots' ability to use color-coded information during flight. The purpose of this study was to determine whether using the Air Force Research Laboratory's (AFRL) Commercial Aviation, Low Intensity, Iteration 2 (CALI-2) LEP spectacles impacts flight performance and normal pilot duties during airborne phases of flight in a general aviation aircraft. Fourteen Instrument-Rated pilots volunteered to complete a series of simulated flights with the CALI-2 LEP spectacles in a variety of simulated flight environments. Overall, the findings suggest that pilots should be able to wear CALI-2 LEP spectacles in real aircraft without affecting their ability to carry out normal pilot duties. Results indicate that pilot participants' ability to follow navigational and flight guidance information and ability to perceive and comprehend color-coded alphanumeric information is preserved when using the CALI-2 LEP spectacles. Questionnaire and interview responses from pilot participants revealed that the LEP spectacles were compatible with displays, controls, and instruments inside the aircraft, and do not substantially hinder visibility of environmental features such as airfield lighting. Implications for these findings in terms of LEP use during real-world flight are discussed, along with future directions for LEP research and implementation in the U.S. National Airspace System (NAS).

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List of Abbreviations

Abbreviation	Definition
AC	Advisory Circular
AFRL	Air Force Research Laboratory
AGL	Above Ground Level
CALI-2	Commercial Aviation, Low Intensity, Iteration 2
CAMI	Civil Aerospace Medical Institute
CDI	Course Deviation Indicator
DIS	Distance to Next Waypoint
EST	Eastern Standard Time
FAA	Federal Aviation Administration
FOV	Field of View
FTE	Flight Technical Error
FUEL QTY GAL	Gallons of Fuel Remaining
IFR	Instrument Flight Rules
ILS	Instrument Landing System
IMC	Instrument Meteorological Conditions
IR	Instrument Rating
KBTV	Burlington International Airport
KOKC	Will Rogers World Airport
LEP	Laser Eye Protection
MFD	Multi-Function Display
MSL	Mean Sea Level
NAS	National Airspace System
NM	Nautical Miles
OAT	Outside Air Temperature
PAPI	Precision Approach Path Indicator
PFD	Primary Flight Display
PIC	Pilot in Command
RMSE	Root Mean Square Error
RWY	Runway
SE	Standard Error

Abbreviation	**Definition**
SM	Statute Miles
SME	Subject Matter Expert
SOP	Standard Operating Procedure
TAGARS	Technically Advanced General Aviation Research Simulator
TIT	Turbine Inlet Temperature
TOST	Two One-Sided T-Test
VFR	Visual Flight Rules

Abstract

Laser strikes are an ever-increasing concern in the civil aviation community and are of particular concern to the Federal Aviation Administration (FAA). They pose a direct threat to aviation safety and air traffic coordination, particularly when they occur during critical phases of flight such as takeoff and landing. Laser strikes cause a variety of negative physiological and psychological effects, including glare, flash blindness, afterimages, and startle (Nakagawara et al., 2003, 2004). Laser eye protection (LEP) spectacles are designed to mitigate these effects by attenuating the visible and infrared light emitted by handheld lasers. While LEP spectacles are effective in mitigating the impacts of laser strikes on pilots, the attenuating properties of the lenses cause a shift in color perception. As such, wearing the LEP spectacles may impact pilots' ability to use color-coded information during flight. The purpose of this study was to determine whether using the Air Force Research Laboratory's (AFRL) Commercial Aviation, Low Intensity, Iteration 2 (CALI-2) LEP spectacles impacts flight performance and normal pilot duties during airborne phases of flight in a general aviation aircraft. Fourteen Instrument-Rated pilots volunteered to complete a series of simulated flights with the CALI-2 LEP spectacles in a variety of simulated flight environments. Overall, the findings suggest that pilots should be able to wear CALI-2 LEP spectacles in real aircraft without affecting their ability to carry out normal pilot duties. Results indicate that pilot participants' ability to follow navigational and flight guidance information and ability to perceive and comprehend color-coded alphanumeric information is preserved when using the CALI-2 LEP spectacles. Questionnaire and interview responses from pilot participants revealed that the LEP spectacles were compatible with displays, controls, and instruments inside the aircraft, and do not substantially hinder visibility of environmental features such as airfield lighting. Implications for these findings in terms of LEP use during real-world flight are discussed, along with future directions for LEP research and implementation in the U.S. National Airspace System (NAS).

Keywords: Laser Strikes, Laser Eye Protection, Aerospace Human Factors, Visual Perception

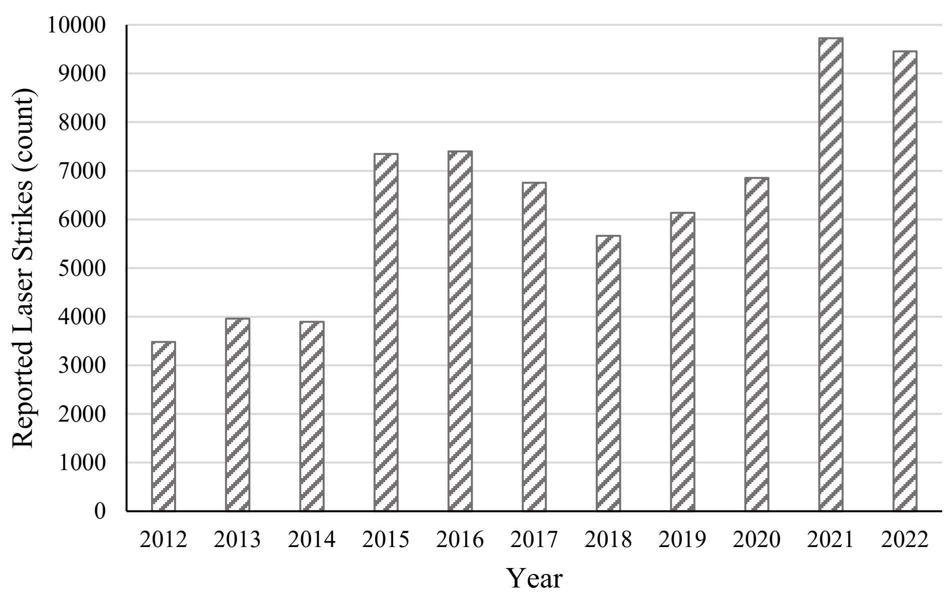
Introduction

Laser strikes are an ever-increasing concern in civil aviation. A laser strike occurs when someone on the ground aims a handheld laser towards an aircraft and illuminates the flight deck. These strikes result in pilots experiencing severe glare, temporary blindness, startle, and—in severe cases—physiological damage to the eyes (Federal Bureau of Investigation, 2014). Experiencing these effects can significantly impact the pilot's ability to read primary flight, navigation, and communication information within the flight deck, see and interact with controls, and detect out-the-window visual information such as airfield lighting and traffic. Such effects on visual performance can in turn affect operational performance, resulting in pilots executing missed approaches and potentially diverting to other airfields (Nakagarawa et al., 2003, 2004). As such, they pose a direct threat to aviation safety and air traffic coordination, particularly when they occur during critical phases of flight such as takeoff, approach, and landing (Nakagawara et al., 2006).

Background

In the last decade, the United States has seen a notable increase in laser strike events reported to the Federal Aviation Administration (FAA); the number of strikes increased from 3,842 incidents in 2012 to nearly 9,500 in 2022. The change represents a roughly 147% increase with nearly 71,000 total laser strikes reported within that ten-year period (Figure 1; FAA, 2023b).

Figure 1
Reported Laser Incidents per Year (FAA, 2023b)



In response to the increasing number of laser strike reports, the United States Congress criminalized the act of pointing a laser at an aircraft in the FAA Modernization and Reform Act of 2012 (P.L. 112-95 § 311) and imposed restrictions on the locations where lasers can be used (FAA, 2011). The FAA further identified specific zones of protected airspace to limit laser use: laser-free zones and critical flight zones (FAA, 2022). Laser-free zones are located within five nautical miles (NM) of the immediate landing area and below 2,000 feet above ground level (AGL). Critical flight zones are located within a 10 NM radius of the airport and below 10,000 feet AGL. Nevertheless, the threat of laser strikes to aviation safety remains, warranting the exploration and implementation of additional risk mitigation strategies.

The FAA has implemented a laser strike reporting system, set forth in Advisory Circular (AC) 70-2B (2020).[1] According to the FAA incident report data, laser strikes occur during both daytime and nighttime flight, with the majority of strikes occurring between 7 pm and 11 pm local time (Nakagawara et al., 2010).[2] Aircraft are susceptible to laser strikes over a wide range of altitudes; however, they have the most severe effects at low altitudes, where critical flight phases such as takeoff, approach, and landing occur. Pilots have reported laser strikes as high as 7,000 feet AGL.

Laser eye protection (LEP) spectacles have been developed as a means of mitigating the deleterious effects of laser radiation (i.e., light) on pilots. These spectacles can protect against the most common handheld visible and near-infrared laser sources and serve as a means to attenuate disruptive or debilitating effects (Garvin et al., 2020). Increasingly, research has evaluated the effects of LEP on the visual perception processes involved in civil aviation. Gildea and Jack (2019) evaluated the impact of LEP spectacles designed to attenuate strikes from green lasers on color perception of light sources commonly used for aviation signal lighting (e.g., Precision Approach Path Indicator [PAPI] lights and runway lighting systems). They found that LEP spectacles caused a shift in color perception; in particular, the accuracy of color detection for white and yellow lights was reduced.

Pierre et al. (2019) evaluated color recognition ability while wearing several different types of LEP spectacles, each with different wavelength absorption properties. They found that color perception tended to shift while wearing the LEP spectacles, but this shift in color perception did not significantly affect color recognition. Notably, Pierre et al. (2019) found that each LEP had unique light transmission characteristics; therefore, the results may not necessarily generalize to all LEP spectacles, particularly those with higher degrees of light transmittance.

Given this evidence for a potential shift in color perception, and subsequent recognition and comprehension of color-coded information in the civil aviation flight environment, it is important to evaluate whether normal pilot duties are impacted by the use of LEP spectacles. To

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[1] Laser incidents can be reported to the FAA at https://www.faa.gov/aircraft/safety/report/laserinfo/report_incident/
[2] See https://www.faa.gov/about/initiatives/lasers/laws

aviate successfully, pilots must monitor a variety of color-coded visual information such as aircraft attitude, airspeed, altitude presented on the Primary Flight Display (PFD), navigation and engine information, radio frequencies for communication and instrument flight procedures, lights and physical controls in the flight deck, and paper materials (e.g., checklists, approach procedure charts). Given the visual complexity of this information, it is important to evaluate whether wearing the LEP spectacles affects the pilots' ability to use this information.

Purpose

The purpose of this study was to determine whether the laser-attenuating properties of the Air Force Research Laboratory's (AFRL) Commercial Aviation, Low Intensity, Iteration 2 (CALI-2) LEP spectacles (Garvin et al., 2020) cause enough of a change in color perception to impact pilot performance during flight. Additionally, pilots' perceptions of usability (e.g., fit, comfortability), and safety during flight were evaluated. The specific research questions that motivated this study were: (a) to what degree are CALI-2 LEP spectacles compatible with flight deck displays, lights, controls, and out-the-window visual information; (b) what effects do CALI-2 LEP spectacles have on pilot performance during approach and landing operations; and (c) what is the usability of CALI-2 LEP spectacles for pilots in terms of form, fit, and function?

Method

Each participant conducted a set of four flights consisting of takeoff, cruise, approach, and landing operations in a simulated civil aviation aircraft. Participants conducted the flights under a variety of ambient lighting and weather conditions, and during normal and non-normal operations. Pilots completed four simulated flight scenarios with and without the CALI-2 LEP spectacles, during which objective measures of pilot performance and subjective measures of usability were recorded. Following the scenarios, pilot participants completed a questionnaire followed by an interview to provide subjective feedback on the effects of the spectacles.

Participants

Fourteen pilots participated in the study in exchange for a cash stipend. Participants were recruited from the Oklahoma City, OK aviation community. Participant age ranged from 19 to 66 years (*M* = 31.79 years, *SD* = 12.10 years) and included 12 men and 2 women (85.7% male). Pilots were eligible to participate in the study if they met following inclusion criteria:

1. Hold an Instrument Rating (IR).
2. Have experience flying a complex, single-engine aircraft.
3. Have experience with Garmin G1000 avionics.
4. Have at least 50 hours of flight time as Pilot in Command (PIC) with at least 10 of those hours under Instrument Flight Rules (IFR).
5. Have flown within last 6 months.

6. Have normal or corrected-to-normal visual acuity (i.e., no eyeglasses; vision must be corrected with contact lenses during study).
7. Have normal color vision.[3]

Across all participants, PIC flight hours ranged from 230 to 7850 (M = 1435.43 hours, SD = 1968.47 hours), with flight hours logged in the last month ranging from 10 to 100 (M = 35.07 hours, SD = 28.25 hours). All participants held more than one pilot certification (see Table 1 for a summary of the pilot certifications held by participants). Two participants (14.29%) reported experiencing at least one laser strike during real-world operations. These participants did not provide information on the physiological or psychological effects of these laser strikes.

Table 1
Pilot Certifications

Pilot Certification Held	Count
Instrument Rating (IR)	14
Commercial Pilot Certificate	11
Multi-Engine Rating	8
Complex Endorsement	8
Private Pilot Certificate	7
High-Performance Endorsement	7
Certified Flight Instructor Rating	4
Tailwheel Endorsement	3
Airline Transport Pilot Certificate	2
Certified Flight Instructor, IR	2
Multi-Engine Instructor Rating	1

Note. All participants held more than one certificate, rating, or endorsement.

Materials

Participant Documents

The following materials were presented electronically via an Apple iPad®:

- Informed Consent form.
- Demographics questionnaire.
- Visual Compatibility Functional Test (see Appendix D).

[3] Participants were screened for normal color vision with a modified Ishihara Color Vision Test (Ishihara, 1972).

Participants were provided the informed consent and demographics questionnaire electronically via Qualtrics®. To support each pre-flight briefing, participants received paper copies of the following (see Appendix B):

- Flight Plan showing weather details for the flight scenario.
- Visual Flight Rules (VFR) map showing route of flight.
- Airport Diagram.
    - Instrument Landing System (ILS) Approach Procedure Chart (Burlington International Airport [KBTV] Runway [RWY] 33).
- Piper Malibu Mirage PA-46 350P Checklist (CheckMate®, n.d.).

Flight Simulator

Simulated flights were conducted in the Civil Aerospace Medical Institute's (CAMI) Technically Advanced General Aviation Research Simulator (TAGARS; see Figure 2). The cockpit and flight dynamics were modeled after a Piper PA 46-350P (Malibu Mirage). Out-the-window visuals were presented using MVRsimulation Virtual Reality Scene Generator® projected onto a 220-degree dome display that surrounded the simulator cab. TAGARS emulated a Garmin G1000 as the primary electronic instrumentation system (see Figure 3). During beta testing, pilot subject matter experts (SMEs) who had real-world experience with a Garmin G1000 determined the color profile of the TAGARS electronic instrumentation system to be similar in appearance to that of a production Garmin G1000.

Figure 2
Flight Deck of the TAGARS Representing a Piper PA 46-350P (Malibu Mirage)

Figure 3

Garmin G1000 Flight Displays as Emulated on TAGARS

Note. PFD shown left; Multi-function Display (MFD) shown right.

CALI-2 LEP Spectacles

The CALI-2 spectacles were designed to filter near-infrared light and visible light produced by green laser pointers. The spectacles are comprised of a proprietary combination of light-absorbing dyes selected to mitigate the transmission of light produced from a 532-nanometer green laser to a pilot's eyes. The CALI-2 spectacles incorporate antireflective coating on the lenses (Garvin et al., 2020). The lenses are molded and fit to small, medium, or large Randolph Engineering® frames and are designed to be compatible with aviation headsets.[4]

Procedures

Each study session lasted approximately five hours. During this time, participants (a) provided informed consent and were given a research briefing, (b) completed a color vision assessment, (c) completed a simulator familiarization session, (d) carried out a series of simulated flights using the CALI-2 spectacles, and (e) provided responses to a usability questionnaire provided by the AFRL and post-task interviews (Appendix C and Appendix D, respectively). The CAMI Institutional Review Board approved all study procedures.

Informed Consent and Research Briefing

Upon arrival, participants read and signed an informed consent document, completed a demographic questionnaire (see Appendix A), and were briefed on the study. During this briefing, participants were given an overview of the research purpose and could ask questions about the research.

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[4] See Garvin et al. (2020) for a complete technical description of the CALI-2 LEP spectacles.

Color Vision Assessment

After the research briefing, participants were screened for normal color vision with a modified Ishihara Color Vision Test under prescribed lighting conditions (Ishihara, 1972).[5] The Ishihara Test consists of a set of test plates filled with colored dots that may be interpreted as (a) containing no pattern, (b) containing numerals, or (c) a path across the plate that is traceable by the participant's finger. Each of the participants interpreted all test plates correctly (which exceeds the test's criteria for normal color vision), so all participants were able to proceed with the study.

Simulator and CALI-2 Spectacles Familiarization

Following the color vision test, participants were fitted with a pair of CALI-2 LEP spectacles (sized small, medium, or large) for use during the study. Participants then received a brief familiarization session with a CAMI simulator engineer that included a walk-through of the cockpit and hands-on interaction with the flight controls and displays. Participants were then asked to perform a 15-minute familiarization flight beginning with the aircraft positioned for takeoff from Will Rogers World Airport (KOKC) Runway 17L. Participants conducted the following maneuvers to aid in familiarization:

- Fly the VFR left traffic pattern, perform a touch-and-go landing, fly a second VFR pattern, and come to a full-stop landing.
- Practice 30- and 45-degree bank turns during the VFR patterns.

Additionally, participants were briefed on the following aircraft settings during each phase of the familiarization flight:

1. Takeoff and Climb
    a. Full throttle.
    b. Mixture set to fully rich.
    c. 10-degree pitch up (roughly 1100 feet/min. climb rate).
2. Level Flight
    a. Mixture set to achieve combustion temperature 10 degrees below max.
    b. Propeller speed set to full.
    c. Manifold pressure at 29 in./hg.
    d. Set throttle to maintain 2500 rpm.
3. Approach
    a. Maintain 100 knots on initial approach.
    b. Maintain 85 knots on final approach and touchdown.

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[5] Participants did not wear the CALI-2 spectacles during the color vision test.

Experimental Session

Following the familiarization session, the participants completed a series of four flight scenarios with and without the CALI-2 spectacles in a variety of weather and lighting conditions, and under different flight operations involving either no malfunctions (normal) or a pilot-correctable alternator breaker malfunction (non-normal) (see Table 2). The sequence of these scenarios was counterbalanced to control for possible order effects. Scenarios consisted of four, approximately 33-minute flights, out of and back to KBVT, Burlington, Vermont. All flights were hand-flown without the use of automated flight control systems (e.g., autopilot, autoland). Participants followed a pre-programmed flight path that included:

- Takeoff from KBTV RWY 19.
- Climb heading 189 to 7000 feet mean sea level (MSL).
- Fly to Middlebury State waypoint (6B0), turn left heading 074 degrees.
- Fly to MPV waypoint, turn left heading 299 degrees.
- Fly to JANUD waypoint, follow ILS approach procedure into KBTV RWY 33.

Before each scenario, the simulator displays and navigation system were configured with:

- Flight plan loaded and activated (KBTV RWY 19 to 6B0 to MPV to KBTV ILS RWY 33; see Appendix B for flight plans).
- ILS frequency set (110.30 MHz for KBTV ILS RWY 33).
- ILS LOC1 Heading in the Course Deviation Indicator (CDI) set (326 degrees).
- Distance Measuring Equipment, Terrain, and Airport Signs turned on in the PFD.

Participants flew the pre-programmed flight path in two lighting and weather environments:

- *Daytime, Overcast:* a daytime scenario with surface winds, cloud coverage, and reduced forward visibility below clouds.
    - Time: 1200 Eastern Standard Time (EST).
    - 90% cloud coverage.
    - 350 feet AGL cloud ceiling, 3000 feet MSL cloud tops, unlimited visibility above clouds.
    - Fog from ground level to 350 feet AGL, forward visibility 2.0 statute miles (SM)
    - Winds heading 206 at 13 knots below 3000 feet.
- *Nighttime, Clear:* a nighttime scenario with calm winds and unlimited ceiling/visibility.
    - Time: 2300 EST.
    - Unlimited ceiling and visibility.
    - Calm winds.

During the Nighttime, Clear flight scenario, a malfunction of the Alternator No. 1 circuit breaker was programmed to occur approximately 7 minutes after takeoff, between takeoff and the 6B0 waypoint. When the malfunction occurred, it manifested on the PFD in two ways: (a) the Crew Alerting System box appeared on the right side of the PFD with “ALTR 1 FAIL” presented in red text on a white background, and (b) "Warning" text appeared on the bottom right of the PFD in white text on a red background. The malfunction served to prompt engagement with displays and controls. Participants were directed to refer to the provided checklist (CheckMate®, n.d.) and follow the procedure for identifying and correcting a malfunction of the Alternator No. 1 circuit breaker. Responses to this failure, as well as the impact of the CALI-2 spectacles on responses, were evaluated in post-flight interviews and questionnaire items. See Figure 4 for an image of the circuit breaker panel located on the overhead panel.

Figure 4
TAGARS Overhead Circuit Breaker Panel

Note. Alternator No. 1 circuit breaker is labeled "ALT 1."

Each of the two environments were flown twice: once while wearing the CALI-2 LEP spectacles and once while not wearing the CALI-2 LEP spectacles. To streamline the study procedure, scenarios were paired together based on flight environment so that each environment was flown back-to-back. After each pair of flights, the experimenter conducted a brief structured interview with the participant over the communication headset about their experience flying with the CALI-2 LEP spectacles (see Appendix C). After the interview, participants completed the Visual Compatibility Functional Test (see Appendix D).

Research Design

Table 2 depicts the independent variables used in the experimental design. Each listed combination of Environment, CALI-2 LEP Spectacles, and Malfunction was flown by participants in a counterbalanced order.

Table 2
Experimental Design of Study (Scenarios)

Environment	CALI-2 LEP Spectacles	Malfunction
Daytime, Overcast	On (Worn)	None
Daytime, Overcast	Off (Not Worn)	None
Nighttime, Clear	On (Worn)	Alternator Breaker
Nighttime, Clear	Off (Not Worn)	Alternator Breaker

Independent Variable

CALI-2 LEP Spectacle Use

The independent variable for this study was the use of the CALI-2 LEP spectacles (i.e., present, absent). This independent variable was evaluated within each of the two Environments (i.e., Daytime, Overcast and Nighttime, Clear). Due to the differences in simulated weather between the two Environments (e.g., winds and overcast clouds only in the scenarios with the Daytime, Overcast Environment); no comparisons were made for LEP spectacle use *between* the two Environments.

Dependent Variables

The usability of the CALI-2 LEP spectacles was evaluated in post-flight interviews (see Appendix C), and through responses to the Visual Compatibility Functional Test (see Appendix D). The impact of CALI-2 spectacles on pilot performance was evaluated with Flight Technical Error (FTE) and responses to on-line probe queries. FTE is the difference between the actual flown flight path and the intended flight path.

Flight Technical Error (FTE)

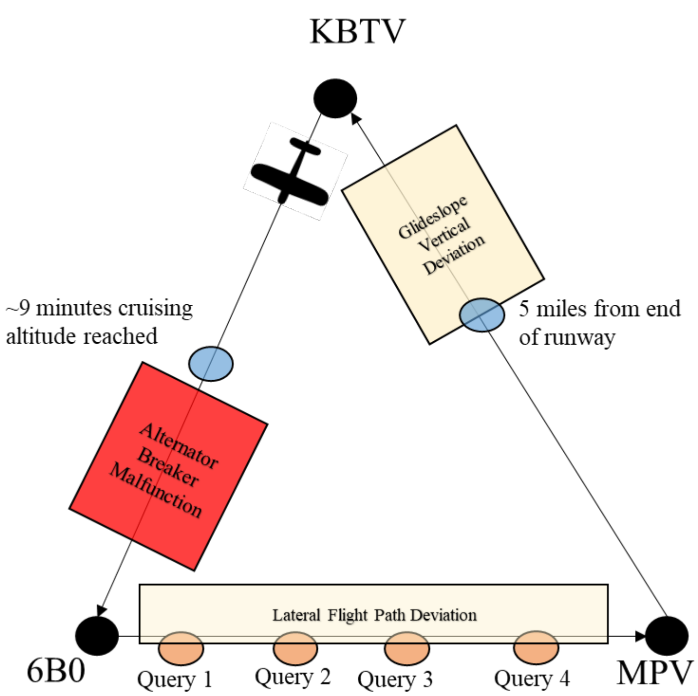
In each flight scenario, FTE was sampled en-route and during the approach of each of the simulated flight scenarios (see Figure 5). To obtain FTE, the root mean square error (RMSE) of the deviation (d) from the planned flight path as measured in the simulator was utilized (see Equation 1). Lateral and vertical FTE (i.e., ILS localizer and ILS glideslope deviations, respectively) were evaluated separately.

During the en-route phase, FTE was sampled for 14.44 SM beginning at 8 SM after the pilot completed the turn at the first waypoint (6B0) and ending at 8 SM before the second waypoint (MPV). The 8 SM buffers were selected to provide adequate distance for the pilot to perform the required heading change and return to the active flight path after turning at 6B0.

During the approach phase, FTE was sampled for 4 SM, beginning at 5 SM from the end of the runway and ending at 1 SM before the end of the runway threshold. Vertical FTE was evaluated using deviation from the ILS glideslope signal and lateral FTE was evaluated using deviation from the ILS localizer signal. Vertical and lateral FTE were compared (a) with and without the CALI-2 LEP spectacles, and (b) separately within each environment. During landing, FTE was measured as the deviation from centerline upon touchdown of both main gears. A two one-sided *t*-test (TOST) procedure was used to determine whether pilot performance while wearing the CALI-2 LEP spectacles was statistically *equivalent* to pilot performance while not wearing the spectacles (See Appendix E).

Figure 5

Dependent Variable Sampling Frames during Flight Scenario



Note. FTE sampling frames are denoted by the yellow boxes. The alternator breaker malfunction (red box) only occurred during the Nighttime, Clear environment.

Equation 1

FTE_{RMSE} from Flight Path Deviation Measured in the Simulator

$$FTE_{RMSE} = \sqrt{\frac{\sum_{i=1}^{n}(d)^2}{n}}$$

Where:

d = instantaneous deviation from center of flight path.
n = number of data points for the deviations from the flight path.

In addition to evaluating FTE during the en-route, approach, and landing phases of flight, flight path tracking performance was also evaluated with respect to the *Instrument Rating Practical Test Standards* set forth by the FAA (2010). These standards identify the criteria for obtaining an IR during an in-flight practical test. For the purposes of this research, the standards against which flight path tracking performance was evaluated are as follows:

1. During the en-route phase of flight, no more than ± 100 feet of vertical deviation from the prescribed cruise altitude.
2. During the approach phase of flight, vertical deviation of no more than 0.75 scale deflection from the center of the glideslope signal.
3. During the approach phase of flight, lateral deviation of no more than 0.75 scale deflection from the center of the localizer signal.

When considering the application of these standards to the present research, it is important to note that the performance demands involved in a real-world, in-flight practical test are far greater than those that were communicated to participants in the present study. Participants were not briefed on these standards during the study and were not instructed to adhere to them.

On-Line Probes

During the second leg of each flight (i.e., between 6B0 and MPV), participants were given on-line probe queries over the headsets using an over-the-radio query procedure adapted from Durso et al. (1998). This procedure, typically applied in evaluations of situation awareness, was adapted for this study to assess participants' perception and comprehension of color-coded alphanumeric information for colors used in aviation environments (i.e., white, red, amber, yellow, green, magenta)[6] while using the CALI-2 spectacles. During the on-line probe procedure, the experimenter asked verbal queries over the headset while the participant flew the aircraft. Specifically, participants were asked to respond verbally with the current values for one of four pieces of aircraft information presented by the flight instrumentation. Participants responded to the following on-line probes after viewing the TAGARS flight displays:

- Outside Air Temperature (OAT).
- Turbine Inlet Temperature (TIT, °F).
- Distance to Next Waypoint (DIS).
- Gallons of Fuel Remaining (FUEL QTY GAL).

Response time and accuracy were measured to assess the pilot's awareness of task-relevant information. The order of the on-line probes was counterbalanced across the study.

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[6] The RGB values for these colors are as follows: White = [0, 0, 0]; Amber = [255, 194, 0]; Yellow = [255, 255, 0]; Green = [97, 194, 91]; Magenta = [255, 0, 255].

Results

FTE

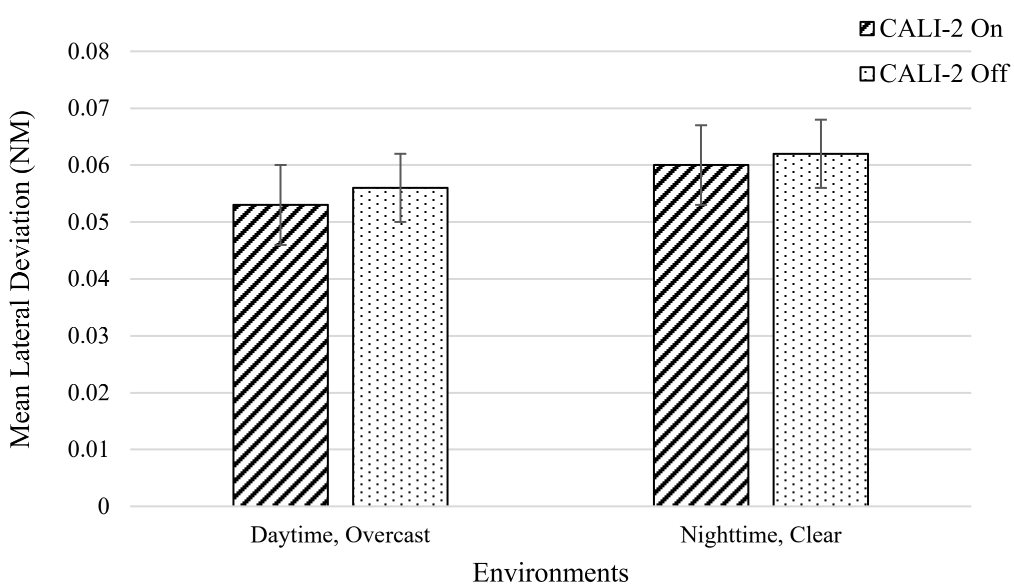
FTE was evaluated for the following phases of flight: (a) lateral deviation during en-route flight, (b) vertical deviation from the ILS glideslope during approach, (c) lateral deviation from the ILS localizer during approach, and (d) lateral deviation from runway centerline during landing.

Lateral Flight Path Deviation During En-Route Flight

The ability of participants to follow the navigational information presented on the PFD was measured by lateral deviation from the prescribed flight path. This was evaluated during the en route phase of flight and between CALI-2 LEP conditions (i.e., with, without). Lateral flight path deviation in NM during the en-route phase was compared between conditions in each flight environment using paired-samples *t*-tests. Statistical equivalence was then evaluated with a follow-up TOST analysis.

Figure 6

Lateral Deviation from Flight Path During En-Route Flight



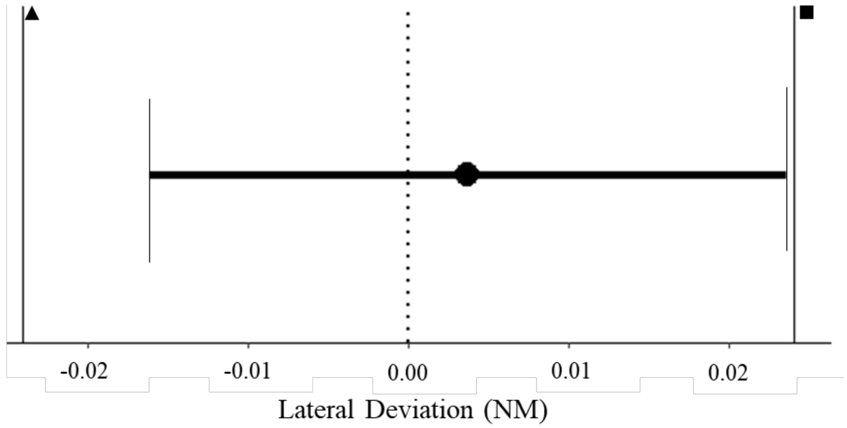
Note. Error bars represent ±1 Standard Error (SE) of the Mean.

Daytime, Overcast

The paired-samples *t*-test indicated no significant difference between wearing and not wearing the CALI-2 LEP spectacles, $t(13) = 0.332$, $p = .745$ (see Figure 6). The follow-on TOST analysis indicated that the observed effect size (Cohen's $d = 0.8$) was significantly within the equivalence bounds of -0.024 and 0.024 NM, $t(13) = -1.81$, $p = .047$ (see Figure 7).

Figure 7

Equivalency Graph for Lateral Flight Path Deviation in the Daytime, Overcast Environment



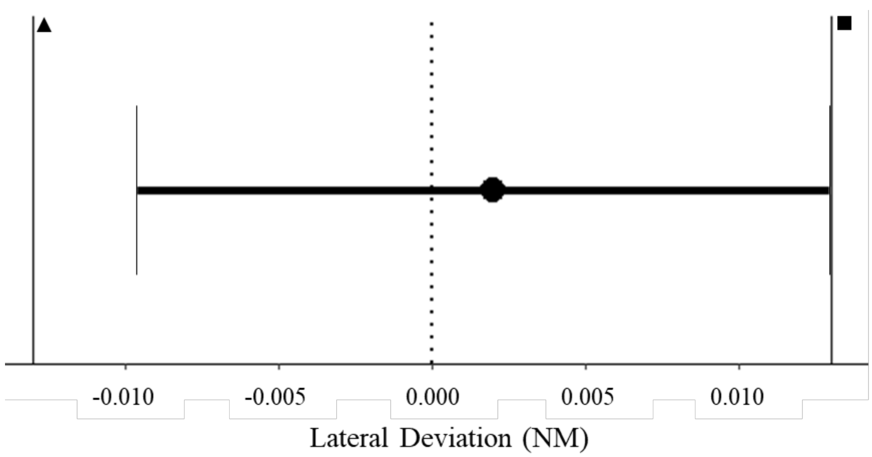
Note. ▲ = Lower Equivalence Bound; ■ = Upper Equivalence Bound; ● = Mean Difference.

Nighttime, Clear

One significant outlier was identified in the Nighttime, Clear scenario using Tukey's Method (Tukey, 1977). The data violated the normality assumption with this outlier included in the analysis; as such, data from this participant was excluded. The paired-samples *t*-test indicated no significant difference in lateral deviation performance between wearing and not wearing the CALI-2 LEP spectacles, $t(12) = 0.270$, $p = .794$ The follow-on TOST analysis indicated that the observed effect size (Cohen's $d = 0.8$) was marginally within the equivalent bounds of -0.013 and 0.013 NM, $t(12) = -1.79$, $p = .049$ (see Figure 8).

Figure 8

Equivalency Graph for Lateral Flight Path Deviation in the Nighttime, Clear Environment



Note. ▲ = Lower Equivalence Bound; ■ = Upper Equivalence Bound; ● = Mean Difference.

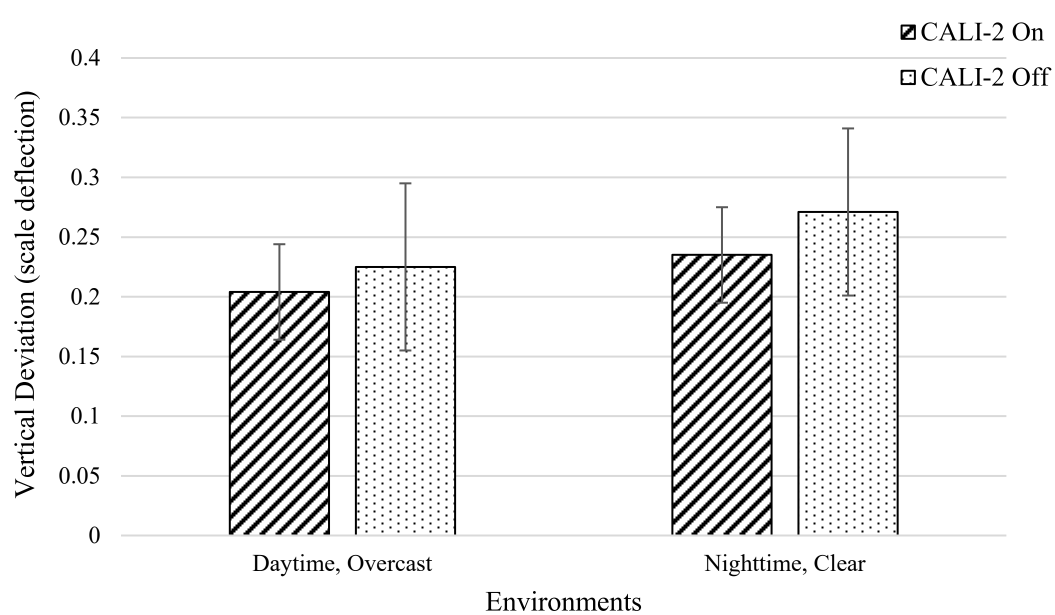
Vertical Flight Path Deviation during Approach

Participants' ability to follow the prescribed vertical profile of the approach with and without the CALI-2 LEP spectacles was evaluated with vertical deviation from the ILS glideslope signal during approach. Vertical deviation was measured on a scale from 0 to 1, with 0 representing no deflection of the glideslope indicator in the PFD, and 1 representing full-scale deflection of the glideslope indicator. Vertical deviation during the approach was compared between conditions using paired samples *t*-tests. Subsequently, vertical deviation data were subjected to follow-on TOST analyses to evaluate statistical equivalence.

Daytime, Overcast

The vertical deviation data collected during the Daytime, Overcast flight environment did not satisfy the assumption of normality; therefore, a logarithmic transformation was applied. Furthermore, vertical deviation data were incomplete for one participant, so data from 13 participants were included in analyses. Vertical flight path deviation did not significantly differ between wearing and not wearing the CALI-2 LEP spectacles, $t(12) = 0.22$, $p = .832$ (see Figure 9). The follow-on TOST analysis indicated that the observed effect size (Cohen's $d = 0.8$) was marginally within the equivalence bounds of -0.357 and 0.357 scale deflection, $t(12) = -1.84$, $p = .045$ (see Figure 10). As such, vertical flight path deviation during approach while wearing the CALI-2 LEP spectacles is statistically equivalent to vertical flight path deviation when they are not worn.

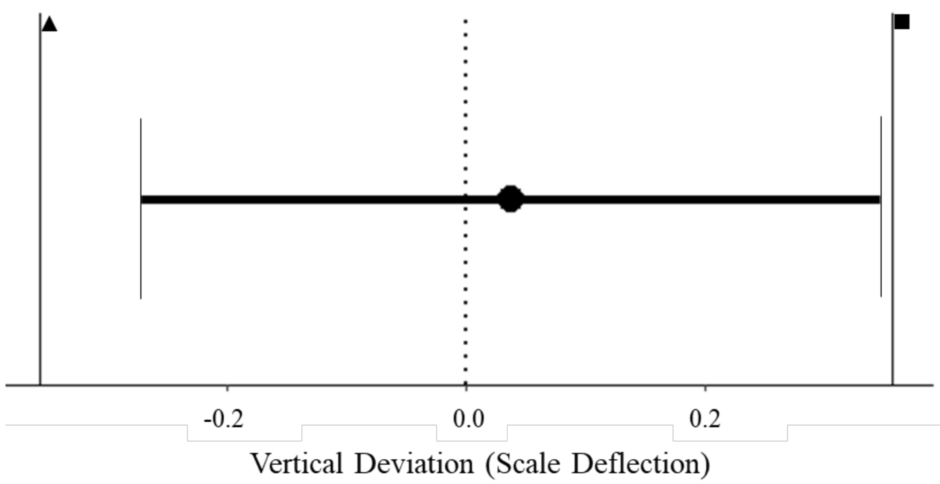
Figure 9
Vertical Deviation from Flight Path during Approach



Note. Error bars represent ±1 Standard Error of the Mean.

Figure 10

Equivalency Graph for Vertical Flight Path Deviation in the Daytime, Overcast Environment



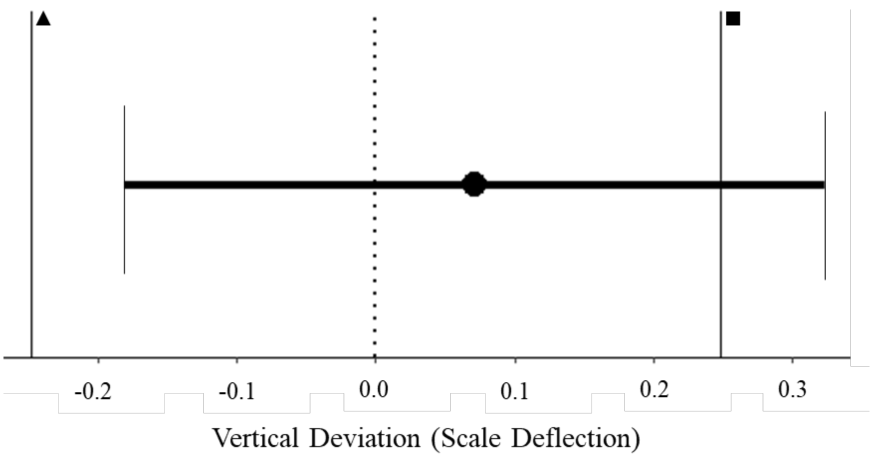
Note. ▲ = Lower Equivalence Bound; ■ = Upper Equivalence Bound; ● = Mean Difference.

Nighttime, Clear

Data from four participants were not included in the analysis of vertical flight path deviation within the Nighttime, Clear environment due to either a simulator malfunction or participant deviation from instructions. As such, data from 10 participants were retained for analyses. There was no significant difference in vertical flight path deviation between wearing and not wearing the CALI-2 LEP spectacles, $t(9) = 0.52$, $p = .618$. The follow-on TOST analysis indicated that the observed effect size (Cohen's $d = 0.8$) was not significantly within the equivalence bounds of -0.248 and 0.248 scale deflection, $t(9) = -1.29$, $p = .115$ (see Figure 11). Therefore, vertical flight path deviation between wearing and not wearing the CALI-2 LEP spectacles cannot be considered statistically equivalent.

Figure 11

Equivalency Graph for Vertical Flight Path Deviation in the Nighttime, Clear Environment



Note. ▲ = Lower Equivalence Bound; ■ = Upper Equivalence Bound; ● = Mean Difference.

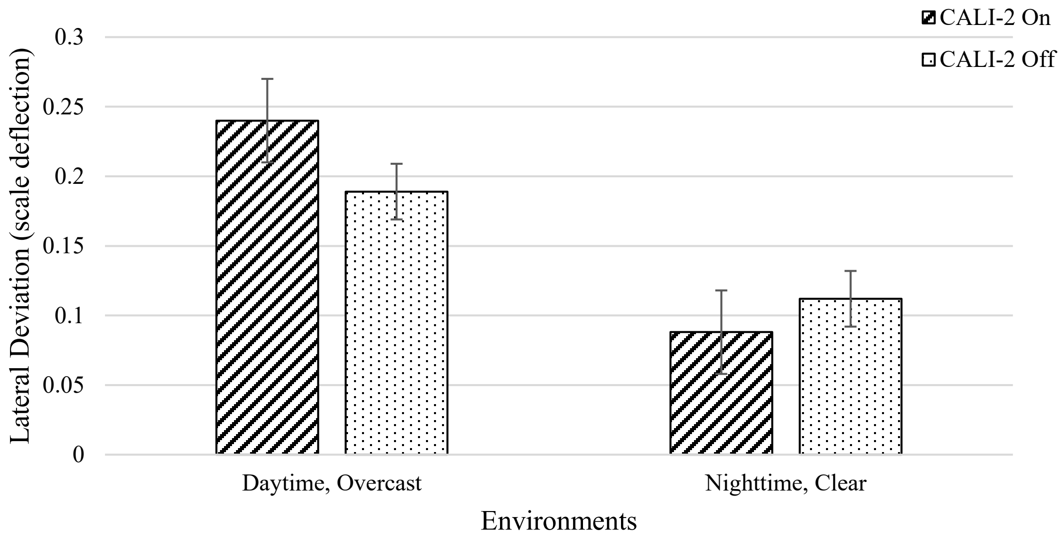
Lateral Flight Path Deviation during Approach

The ability of participants to follow the prescribed lateral profile of the approach was evaluated by lateral deviation from the ILS localizer signal during approach and compared between wearing and not wearing the CALI-2 LEP spectacles. Lateral deviation was measured on a scale from 0 to 1, with 0 representing no deflection of the localizer deviation indicator and 1 representing full-scale deflection of the localizer deviation indicator. Lateral deviation during the approach was compared between CALI-2 LEP conditions using paired-samples *t*-tests. Subsequently, lateral deviation data were subjected to follow-on TOST analyses to evaluate statistical equivalence.

Daytime, Overcast

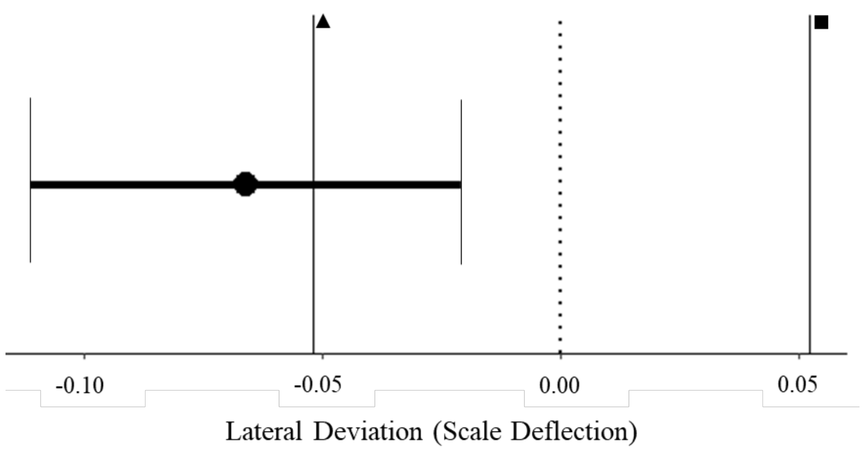
ILS lateral deviation data in the Daytime, Overcast environment were not collected for one participant due to a simulator malfunction; therefore, data from 13 participants was retained for analyses. There was a significant difference between lateral flight path deviation during approach as a function of CALI-2 LEP spectacle use in the Daytime, Overcast environment, $t(12) = -2.60$, $p = .023$. Lateral deviation was greater when participants wore the CALI-2 LEP spectacles than when they did not (see Figure 12). The follow-on TOST analysis indicated that the observed effect size (Cohen's $d = 0.8$) was not significantly within the equivalence bounds of -0.052 and 0.052 scale deflection, $t(12) = -0.55$, $p = .703$ (see Figure 13). As such, statistical equivalence cannot be established. While no direct comparisons were made between the Daytime, Overcast and Nighttime, Clear environments, it important to note that the mean lateral deviation values in the Daytime, Overcast environment were elevated. This is likely due to the 13 knot winds (which resulted in a 10.8 knot crosswind component) being present during the approach and landing phases of flight, which likely increased the difficulty of following the lateral guidance during the approach.

Figure 12
Lateral Deviation from Flight Path during Approach



Note. Error bars represent ±1 Standard Error of the Mean.

Figure 13
Equivalency Graph for Lateral Deviation from ILS Localizer Signal within the Daytime, Overcast Environment



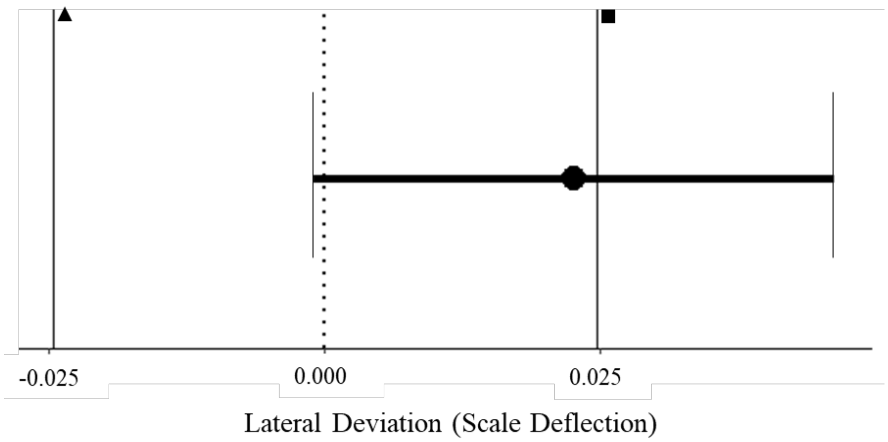
Note. ▲ = Lower Equivalence Bound; ■ = Upper Equivalence Bound; ● = Mean Difference.

Nighttime, Clear

Lateral deviation data during approach were incomplete for three participants, resulting in data for 11 participants being included in analyses. In the Nighttime, Clear environment, there was no significant difference in lateral flight path deviation during approach between wearing and not wearing the CALI-2 LEP spectacles, $t(10) = 1.73$, $p = .114$. The follow-on TOST analysis indicated that the observed effect size (Cohen's $d = 0.8$) was not significantly within the equivalence bounds of -0.025 and 0.025 scale deflection, $t(10) = -0.16$, $p = .439$ (see Figure 14). As with the non-significant result from the initial t-test, the non-significant TOST test indicates that statistical equivalency is undetermined (see Appendix E for further discussion on undetermined outcomes).

Figure 14

Equivalency Graph for Lateral Deviation from Flight Path in the Nighttime, Clear Environment



Note. ▲ = Lower Equivalence Bound; ■ = Upper Equivalence Bound; ● = Mean Difference.

Deviation from Runway Centerline at Touchdown

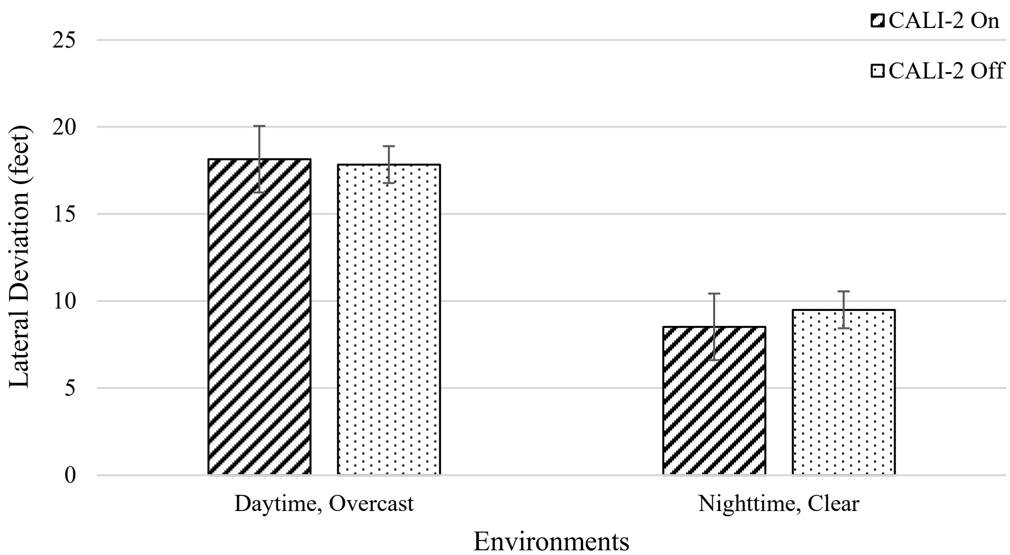
The impact of wearing the CALI-2 LEP spectacles on landing performance was evaluated with deviation (in feet) from the runway centerline at touchdown. Lateral deviation from the runway centerline was compared within each environment using paired-samples t-tests and follow-on with a TOST analysis to evaluate statistical equivalence.

Daytime, Overcast

Landing data for one participant in the Daytime, Overcast environment were incomplete, so data for 13 participants were retained for analysis. In the Daytime, Overcast environment, there was no significant difference in lateral deviation from runway centerline at touchdown between wearing and not wearing the CALI-2 LEP spectacles, $t(12) = -0.23$, $p = .823$ (Figure 15). The follow-on TOST analysis indicated that the observed effect size for deviation from centerline (Cohen's $d = 0.8$) was significantly within the equivalence bounds of -2.861 and 2.861 feet, $t(12) = 1.83$, $p = .046$ (see Figure 16). As such, statistical equivalence was established.

Figure 15

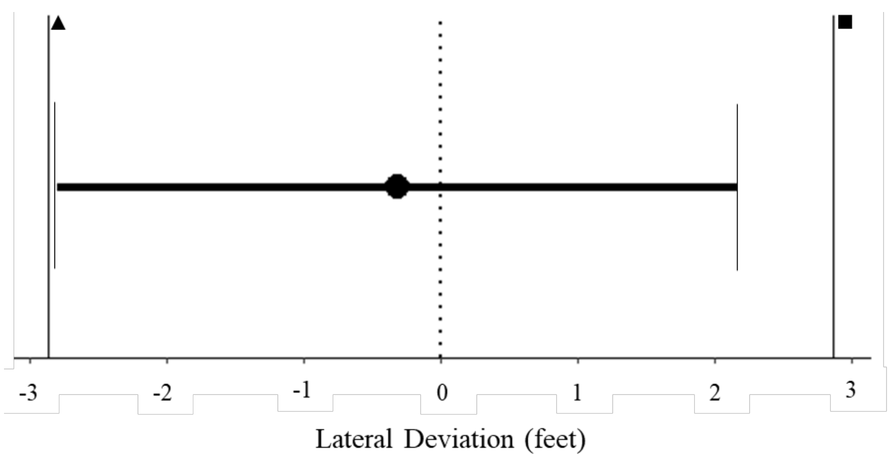
Lateral Deviation from Runway Centerline at Touchdown



Note. Error bars represent ±1 Standard Error of the Mean.

Figure 16

Equivalency Graph for Lateral Deviation from Runway Centerline at Touchdown in the Daytime, Overcast Environment

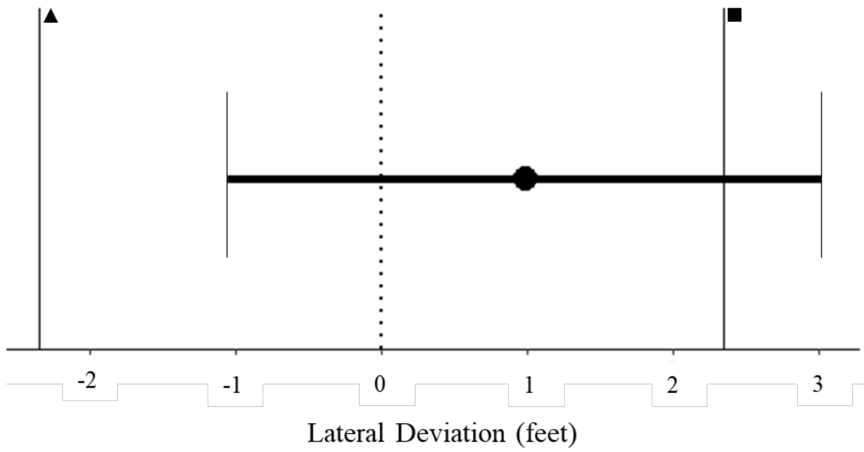


Note. ▲ = Lower Equivalence Bound; ■ = Upper Equivalence Bound; ● = Mean Difference.

Nighttime, Clear

Landing data for one participant in the Nighttime, Clear environment were incomplete, so data for 13 participants were retained for analysis. In the Nighttime, Clear environment, there was no significant difference in lateral deviation from runway centerline at touchdown between wearing and not wearing the CALI-2 LEP spectacles, $t(12) = 0.86$, $p = .404$ (see Figure 15). The follow-on TOST analysis indicated that the observed effect size for deviation from centerline (Cohen's $d = 0.8$) was not significantly within the equivalence bounds of -2.34 and 2.34 feet, $t(12) = -1.19$, $p = .128$ (see Figure 17). As such, statistical equivalence was not established.

Figure 17
Equivalency Graph for Lateral Deviation from Runway Centerline at Touchdown in the Nighttime, Clear Environment



Note. ▲ = Lower Equivalence Bound; ■ = Upper Equivalence Bound; ● = Mean Difference.

Instrument Rating Practical Test Standards

According to the *Instrument Rating Practical Test Standards* set forth by the FAA (2010), an instrument-rated pilot should not exceed more than ± 100 feet of vertical deviation during the en-route phase of their in-flight practical test. Across all flight scenarios where the CALI-2 LEP spectacles were used, 12 flights (44.44%) exceeded this standard. Across all flight scenarios with CALI-2 LEP spectacles not worn, 11 flights (40.74%) exceeded this standard. When comparing between CALI-2 LEP conditions using a McNemar Change Test, the two distributions were determined to be statistically equal, X^2 (1, 54) = 0.35, $p = 0.556$.

An instrument-rated pilot should not exceed a vertical deviation of more than 0.75 scale deflection during the approach phase of their in-flight practical test. Applying these standards in the current study, one approach (4.00%) exceeded these standards while using the CALI-2 LEP spectacles. Given the single data point, no additional analysis was conducted. Six approaches (23.08%) exceeded these standards while not using the CALI-2 LEP spectacles. A paired-samples McNemar Change analysis revealed that there were significantly more deviations from the standard in flights with CALI-2 LEP spectacles not worn than in flights with CALI-2 LEP spectacles worn, X^2 (1, 51) = 9.63, $p = .002$.[7]

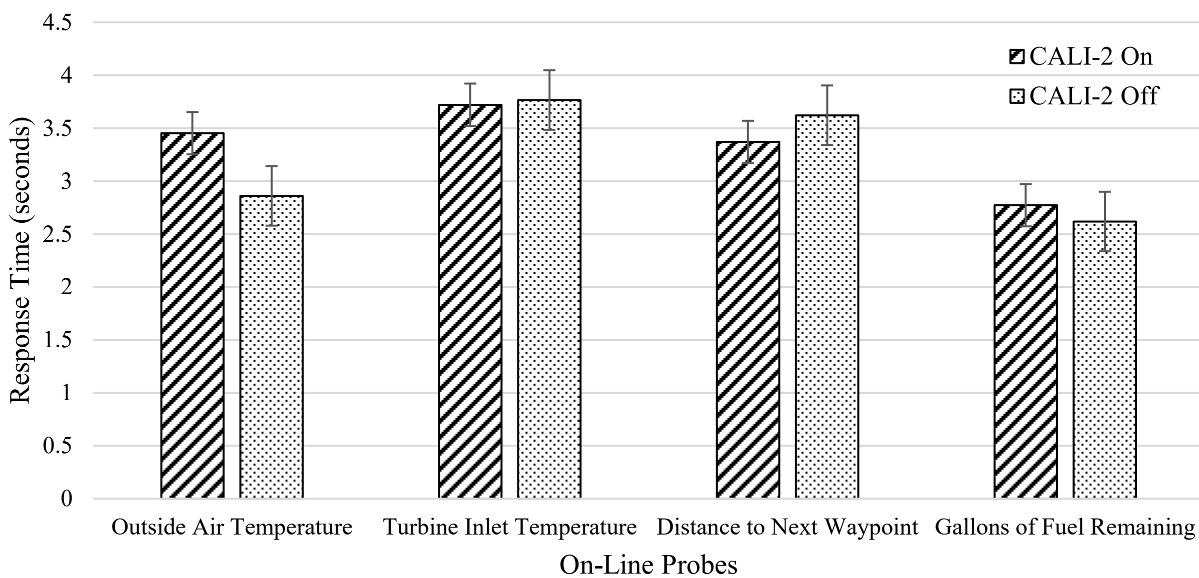
[7] All but one participant's deviations that exceeded the standards were at the beginning or at the end of the glideslope data capture interval.

On-Line Probes

During the en-route phase of each flight, participants responded to over-the-headset verbal queries from an experimenter requesting information presented on the displays (see Research Design section). Responses were evaluated for their accuracy and response time. Response time was measured from the point when the experimenter finished verbalizing the query to the point when the participant finished verbalizing a response. All participants provided correct responses. Response time was averaged between the two environments, creating a single value to compare between wearing and not wearing the CALI-2 LEP spectacles. Mean response times for each query and CALI-2 LEP condition are shown in Figure 18.

A one-way, within-subjects Analysis of Variance (ANOVA) was performed to compare participant responses between wearing and not wearing the CALI-2 LEP spectacles for each of the four probes. The ANOVA revealed that response times to each probe did not significantly differ between CALI-2 LEP conditions ($p > .05$, in each case; see Table 3). These results suggest that perception and comprehension of color-coded alphanumeric information in the flight deck is preserved while wearing the CALI-2 LEP spectacles.

Figure 18
Mean Response Time for Each On-line Probe Query



Note. Error bars represent ±1 Standard Error of the Mean.

Table 3
On-line Probe Response Times Comparing With or Without CALI-2

Probe	*F*-statistic	*p*-value
OAT	$F(1, 13) = 0.803$	$p = 0.386$
TIT	$F(1, 13) = 0.023$	$p = 0.881$
Waypoint	$F(1, 13) = 0.496$	$p = 0.494$
Fuel	$F(1, 13) =0.921$	$p = 0.355$

Note. Probe text color and background in this table approximate the color and background presented on the simulator displays.

Visual Compatibility Functional Test

The responses to a six-point Likert scale to the Visual Compatibility Functional Test indicate that, overall, participants found the CALI-2 LEP spectacles to be satisfactory in term of compatibility with normal pilot duties and in term of form, fit, and function (Table 4). In particular, participants were generally satisfied with the compatibility between the CALI-2 LEP spectacles and color displays (Figure 19), particularly regarding Warning, Caution, and Advisory Lights (i.e., reds, greens, yellows; Figure 20). Participants were also generally satisfied with visibility of switches, text, and physical controls in the flight deck while wearing the CALI-2 LEP spectacles (there was one "marginally unsatisfactory" response in the Daytime, Overcast environment). Participants were instructed to provide written comments when they responded as "Marginally Satisfactory" or lower (see Figure 21; see Table 5 for specific comments).

Table 4
Responses for the Visual Compatibility Functional Test Questions by Flight Environment

Question Prompt	**Daytime, Overcast** Mean (SD)	**Nighttime, Clear** Mean (SD)
Compatibility with color displays (i.e., smart phone, tablet, computer, etc.).	5.57 (0.51)	5.57 (0.51)
Compatibility with Warning, Caution, and Advisory Lights (Reds, Greens, Yellows).	5.50 (0.52)	5.64 (0.50)
Color, contrast, and visibility of surfaces. Includes switches, rotary dials, printed words and symbols as well as kneeboard maps and other materials.	5.36 (0.93)	5.57 (0.85)
Color, contrast, and visibility of terrain colors and geographical features (not a display).	5.50 (0.52)	4.86 (1.03)

Question Prompt	**Daytime, Overcast** Mean (SD)	**Nighttime, Clear** Mean (SD)
Performance of normal duties are not hindered nor impaired to the extent as to interfere with safety or mission completion.	5.57 (0.51)	5.64 (0.50)
Rate any anticipated impact on detection, recognition, identification, and tracking of targets to the extent as to interfere with safety or mission completion.	5.50 (0.52)	5.50 (0.65)
Field of view, any interference or obstruction with the LEP glasses frame or lenses.	5.57 (0.51)	5.64 (0.63)
Field of view, any interference or obstruction with the visual line of sight to any instrument or display that is critical to normal flight tasks.	5.57 (0.51)	5.50 (0.65)
Rate personal safety while utilizing LEP glasses.	5.57 (0.65)	5.50 (0.65)
Overall transmission of the LEP glasses in terms of visibility (too bright? Too dark?).	5.07 (1.07)	5.14 (0.77)
Any distortions or distractions (reflections) that hinder or impair visual performance to the extent as to interfere with safety or flight completion.	5.43 (0.51)	5.50 (0.52)
Contrast and visibility of the scene outside.	5.43 (0.76)	5.00 (1.04)
Please rate your overall visual acuity (ability to read small text and symbols) with the LEP glasses.	5.64 (0.63)	5.43 (0.94)
The overall comfort of the LEP glasses.	5.21 (0.70)	5.50 (0.52)
The ease of putting on and taking off the LEP glasses.	5.43 (0.65)	5.50 (0.52)
The ability of the LEP glasses to stay in place while worn during normal operations.	5.57 (0.51)	5.43 (0.65)
Your confidence for safe and effective operation with the LEP glasses.	5.50 (0.65)	5.36 (0.75)

Note. Participants responded on a six-point scale that ranged from "Very Unsatisfactory" to "Very Satisfactory." The Visual Compatibility Functional Test questionnaire is provided in Appendix D.

Figure 19
Question 1: Compatibility with Color Displays (i.e., Smart Phone, Tablet, Computer, etc.)

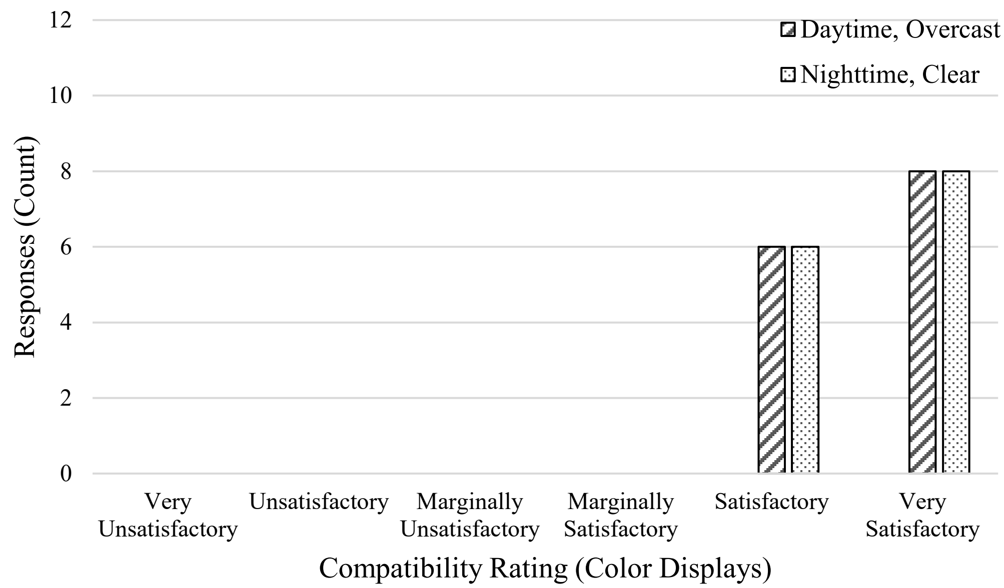
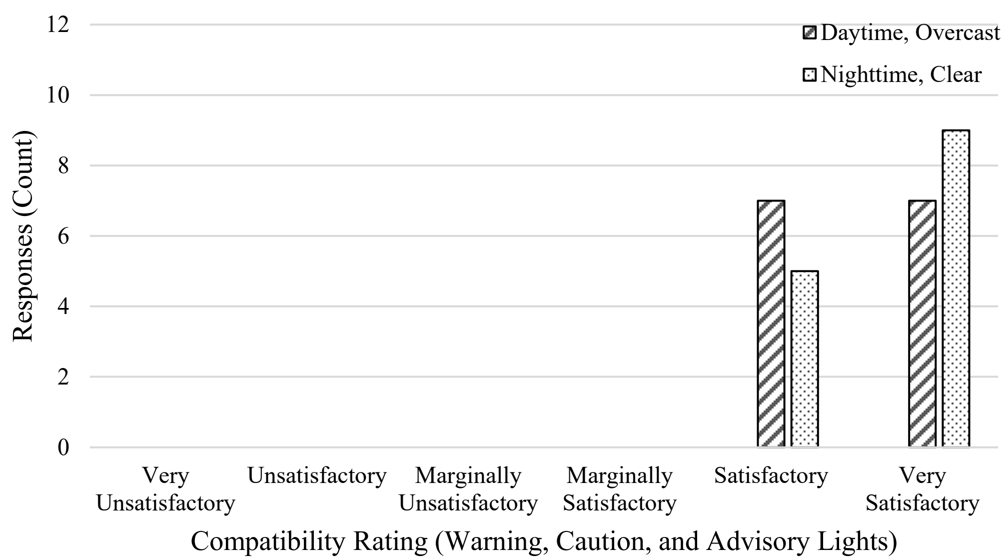


Figure 20
Question 3: Compatibility with Warning, Caution, and Advisory Lights (Reds, Greens, Yellows)[8]



[8] Question 2 of the Visual Compatibility Functional Test was omitted because there were no monochromatic displays used in this study.

Figure 21

Question 4: Color, Contrast and Visibility of Surfaces. Includes Switches, Rotary Dials, Printed Words and Symbols as well as Kneeboard Maps and Other Materials

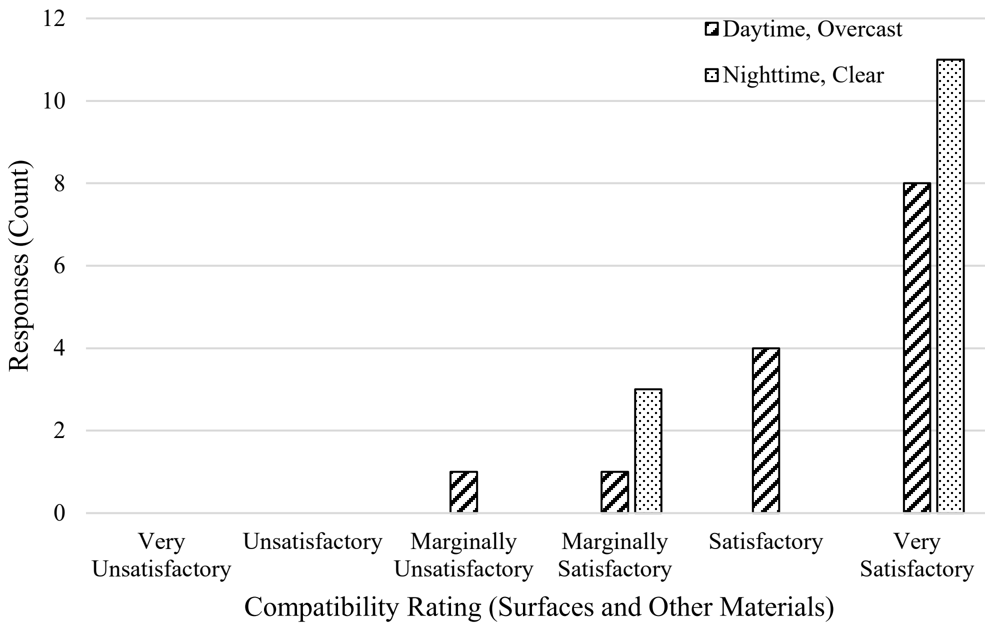


Table 5

Participant-provided Comments to Question 4

Environment	Comments for Less Than Satisfactory Response
Daytime, Overcast	It was harder to read smaller numbers and letters.
Nighttime, Clear	It was harder to see the circuit breakers at night.
Nighttime, Clear	The paper approach plate was slightly harder to read when the lighting was uneven. I felt that I had to remove the glasses to clarify what I was reading. This could be due to lack of familiarity. Aside from that, glasses did not pose any issues.
Daytime, Overcast	I just felt like it was a little it harder to read the check list. Everything else seemed to be fine
Nighttime, Clear	Was even harder to read the text on the checklist in my opinion.

Participants were generally satisfied with color, contrast, and visibility of terrain and geographical features during flights in the Daytime, Overcast environment. One participant provided a “Marginally Unsatisfactory” rating for these features in the Nighttime, Clear environment (Figure 22; see Table 6 for specific comments).

Figure 22

Question 5: Color, Contrast and Visibility of Terrain Colors and Geographical Features (Not a Display)

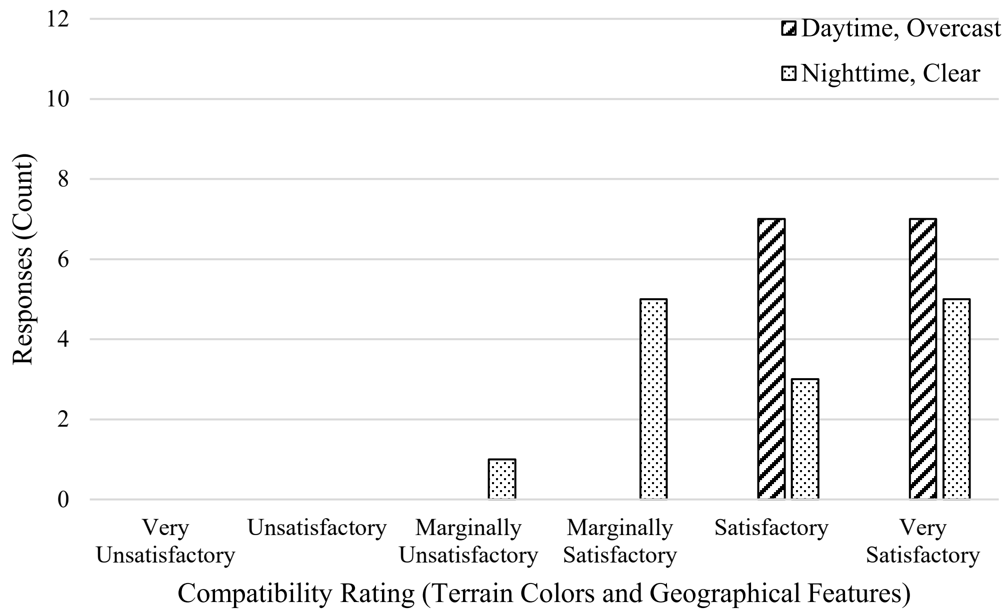


Table 6

Participant-provided Comments to Question 5

Environment	Comments for Less Than Satisfactory Response
Nighttime, Clear	It was harder to see the terrain at night.
Nighttime, Clear	Instrument panel was very bright compared to outside, would have liked to turn down the brightness however I can’t tell if the glasses affected the apparent dimness of the terrain.
Nighttime, Clear	Outside terrain features had a sort of tint/darker feeling than without the glasses on.
Nighttime, Clear	When putting on the lenses, I noticed a darker tint immediately. This environment is not as dark as real world. I would feel slightly uncomfortable flying in the mountains at night without shaded glasses. I feel the shade may further make terrain harder to see. In non-mountain areas, I wouldn’t feel as uncomfortable to wear them.

Environment	Comments for Less Than Satisfactory Response
Nighttime, Clear	The runway lights during landing with the glasses on looked large and blurry which could affect the approach path at night. Could be sim visuals, but if it is the same in real life, would not be optimal.
Nighttime, Clear	Harder to see the terrain at night with the glasses on.

In general, participants responded that the LEP spectacles were satisfactory in terms of compatibility with piloting tasks (see Figure 23 through Figure 27; see Table 7 through Table 11 for specific comments). Personal safety while wearing the CALI-2 LEP spectacles was generally rated as satisfactory (see Figure 24; see Table 7 for specific comments). One participant reported that the overall transmission of the CALI-2 LEP spectacles in terms of visibility was "Unsatisfactory" (Figure 28; see Table 12 for specific comments).

Figure 23

Question 6: Performance of Normal Duties is Not Hindered or Impaired to the Extent as to interfere with Safety or Mission Completion

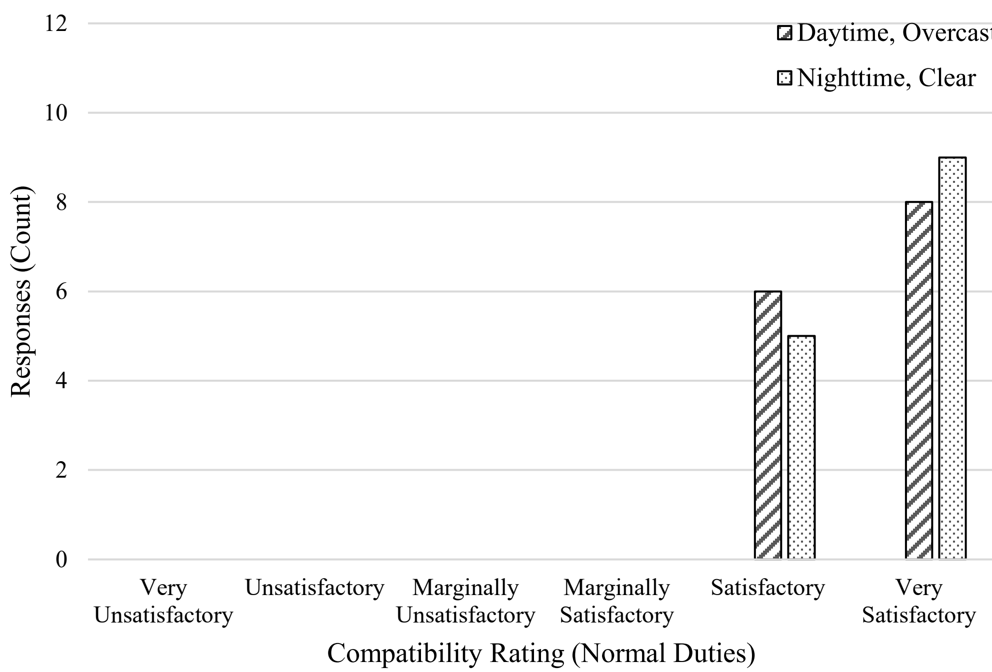


Figure 24

Question 7: Rate Personal Safety while Utilizing LEP Glasses

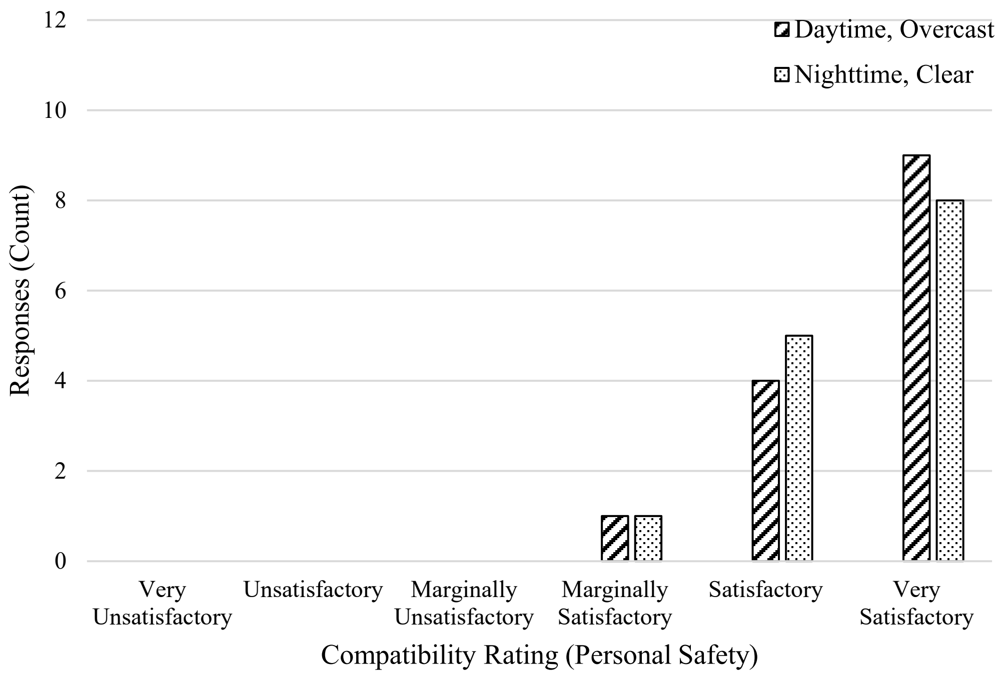


Table 7

Participant-provided Comments to Question 7

Environment	Comments for Less Than Satisfactory Response
Daytime, Overcast	I don't normally wear sunglasses when I fly so the darker shade made it a little bit harder for me.
Nighttime, Clear	I feel safer without the glasses on.

Table 8

Participant-provided Comments to Question 7: Note any Hazards[9]

Environment	Comments for Less Than Satisfactory Response
Daytime, Overcast	Traffic detection might be harder.
Daytime, Overcast	Potential fogging, none experienced while flying.
Daytime, Overcast	None.

[9] Two-part question item in the Visual Compatibility Functional Test were divided into separate items for this evaluation.

Environment	Comments for Less Than Satisfactory Response
Daytime, Overcast	During the day, the glasses have a sort of haze layer similar to wearing a pair of tinted, colored sunglasses. This during the day causes a discoloration of the clouds and horizon but not enough for me to have felt unsafe.
Daytime, Overcast	Only thing that was slightly different is if there was a shadow on the approach chart. Slightly darker or a higher contrast. Day flight not as noticeable.
Daytime, Overcast	None.
Daytime, Overcast	Possibly being blinded by the Sun without darker lenses.
Nighttime, Clear	Harder to see outside at night and harder to see things not lit up inside the cockpit.
Nighttime, Clear	None.
Nighttime, Clear	Noticed a slight amount of dizziness after removing the glasses after the night flight.
Nighttime, Clear	Field of view is really good, similar to wearing a nice pair of sunglasses. I was able to see all instruments I needed to during the flight.
Nighttime, Clear	Just reading paper approach plates using a light that creates shadows.
Nighttime, Clear	During flight when abnormal conditions occur (alternator 1 breaker tripped) and I was focusing on items not in my normal field of view there was a slight distraction from the edge of the glasses/lenses. I would attribute this to my personal preference of keeping my eyes forward towards flight instruments while diagnosing and fixing the abnormality.
Nighttime, Clear	None observed.
Nighttime, Clear	Unlit objects at night are harder to see, than without.

Figure 25

Question 8: Rate any Anticipated Impact on Detection, Recognition, Identification, and Tracking of Information to the Extent as to Interfere with Safety or Mission Completion

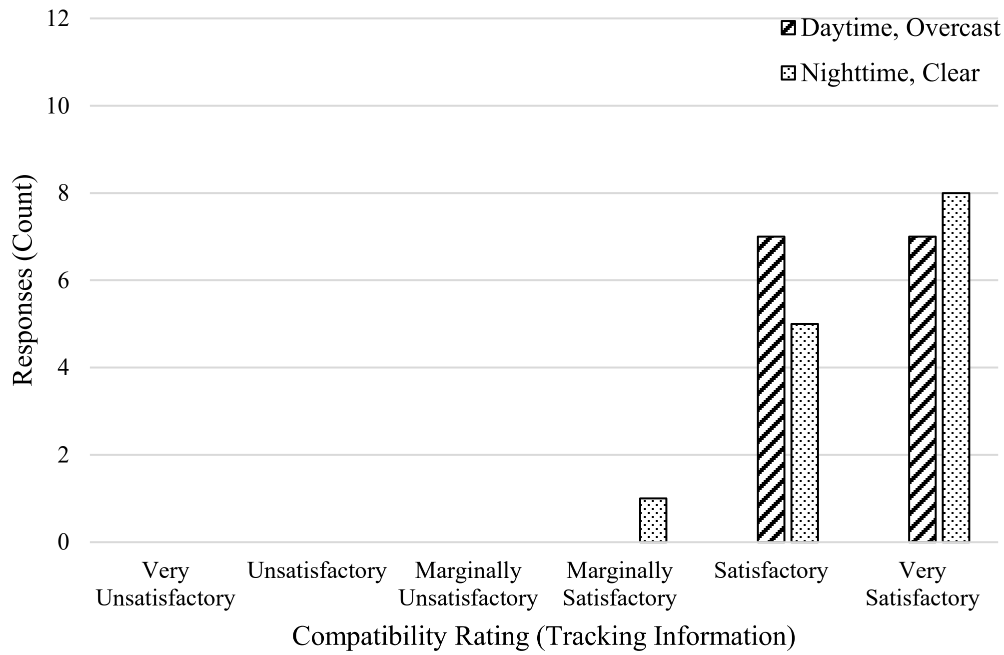


Table 9

Participant-provided Comments to Question 8

Environment	Comments for Less Than Satisfactory Response
Nighttime, Clear	It was harder to see the circuit breakers and things not lit up inside the cockpit

Figure 26

Question 9: Field of View (FOV), Any Interference or Obstruction with the LEP Glasses Frame or Lenses

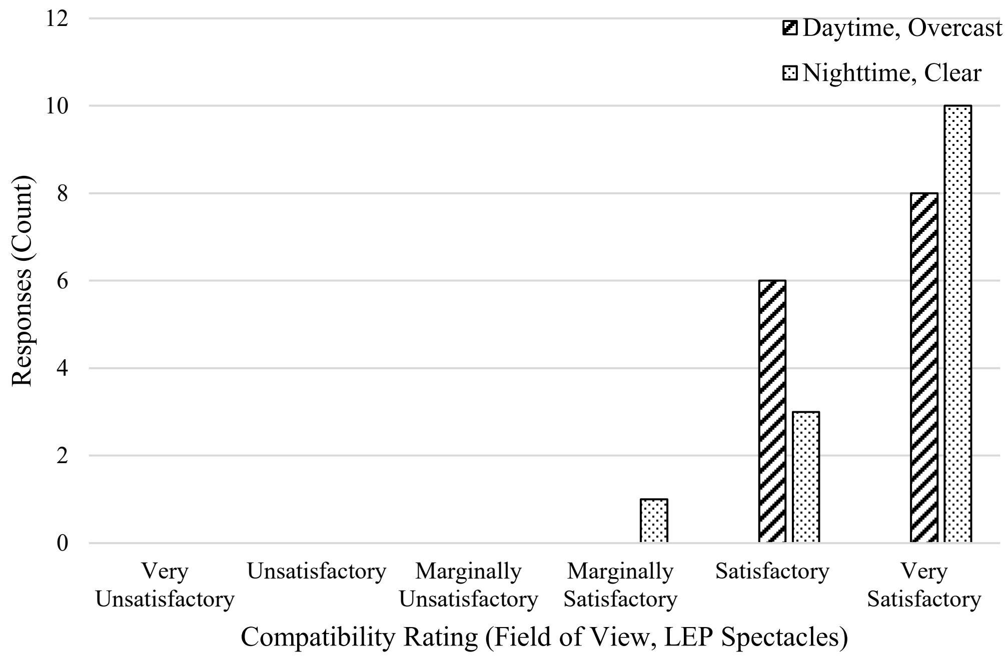


Table 10

Participant-provided Comments to Question 9

Environment	Comments for Less Than Satisfactory Response
Nighttime, Clear	During flight when abnormal conditions occur (alternator 1 breaker tripped) and I was focusing on items not in my normal field of view there was a slight distraction from the edge of the glasses/lenses. I would attribute this to my personal preference of keeping my eyes forward towards flight instruments while diagnosing and fixing the abnormality.

Figure 27
Question 10: FOV, Any Interference or Obstruction with the Visual Line of Sight to any Instrument or Display that is Critical to Normal Flight Tasks

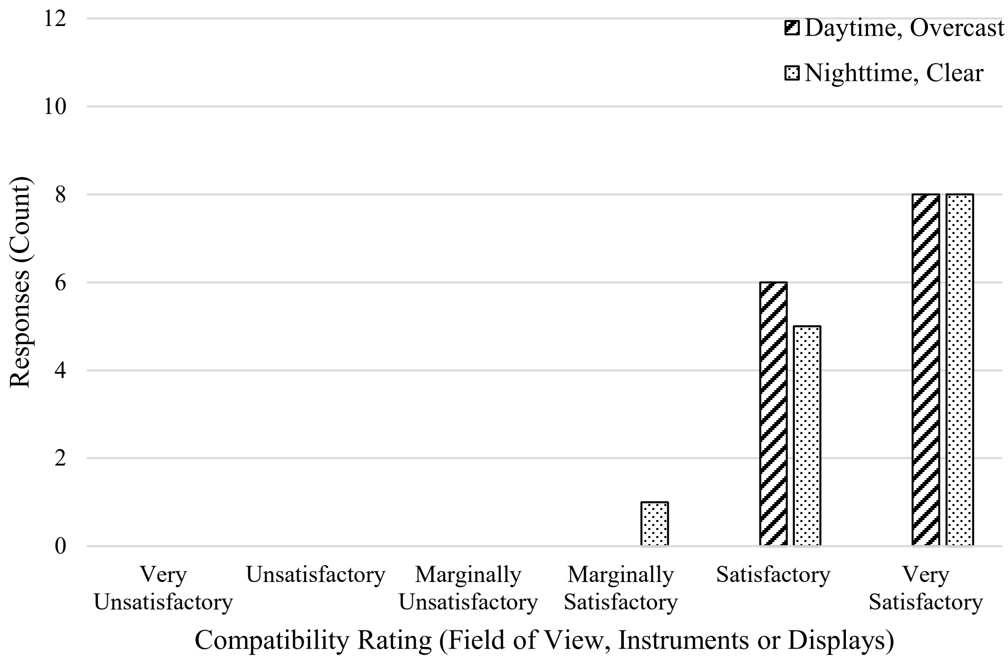


Table 11
Participant-provided Comments to Question 10

Environment	Comments for Less Than Satisfactory Response
Nighttime, Clear	It [m]ay be more of a simulator issue … I never saw the hazard or wire alerted by the simulator. But then on the second without glasses check, I didn't see it either … it would be good to view a real hazard or wire with the glasses to better evaluate.

Figure 28

Question 11: Overall Transmission of the LEP Glasses in Terms of Visibility (Too Bright? Too Dark?)

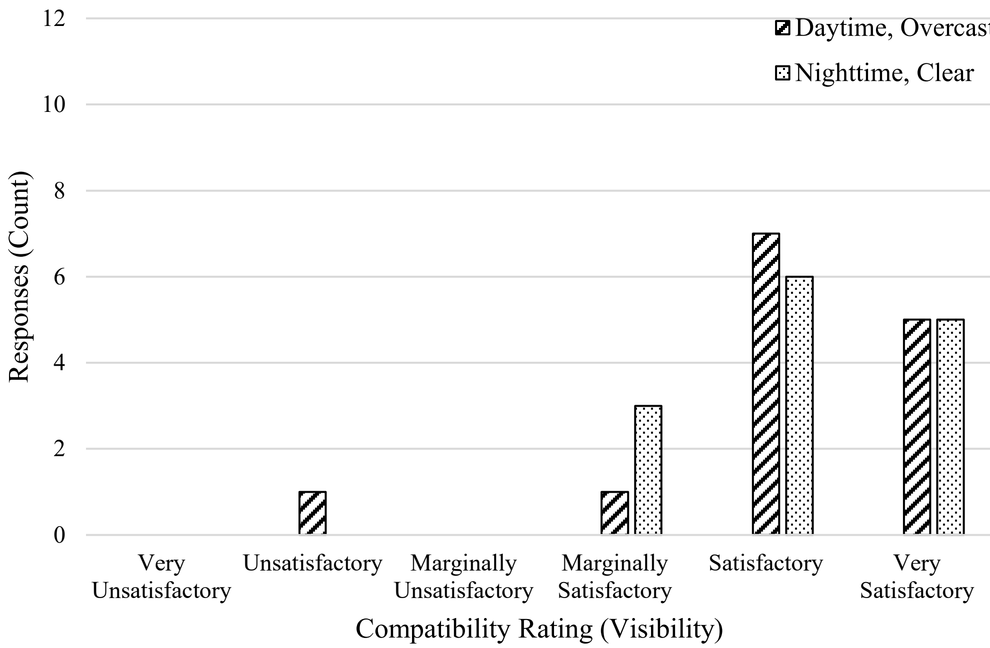


Table 12

Participant-provided Comments to Question 11

Environment	Comments for Less Than Satisfactory Response
Daytime, Overcast	I don't wear sunglasses when I fly so it was a little too dark for me
Daytime, Overcast	I would personally choose a slightly darker lens shade for flight in daytime IMC[10] due to the brightness I have experienced in the top one thousand feet of clouds. The lenses I normally fly with are approximately 30% light transmission.
Nighttime, Clear	I liked how it made the panel a little less bright and easier to look at but could see how that would make me tired if I had not had enough sleep
Nighttime, Clear	Tint may be too dark to see outside at night.
Nighttime, Clear	A bit dark at night

[10] i.e., instrument meteorological conditions.

Participants rated any distortions or distractions on an agreement scale (Very Unsatisfactory to Very Satisfactory; Figure 29). All but one participant indicated the out-the-window view was at least satisfactory (see Figure 30; see Table 13 for specific comments). However, it must be noted that the out-the-window view was simulated. Participant responses also suggest that the ability to read with the CALI-2 LEP was satisfactory (see Figure 31; see Table 14 for specific comments).

Figure 29

Question 12: Any Distortions or Distractions (Reflections) that Hinder or Impair Visual Performance to the Extent as to Interfere with Safety or Flight Completion

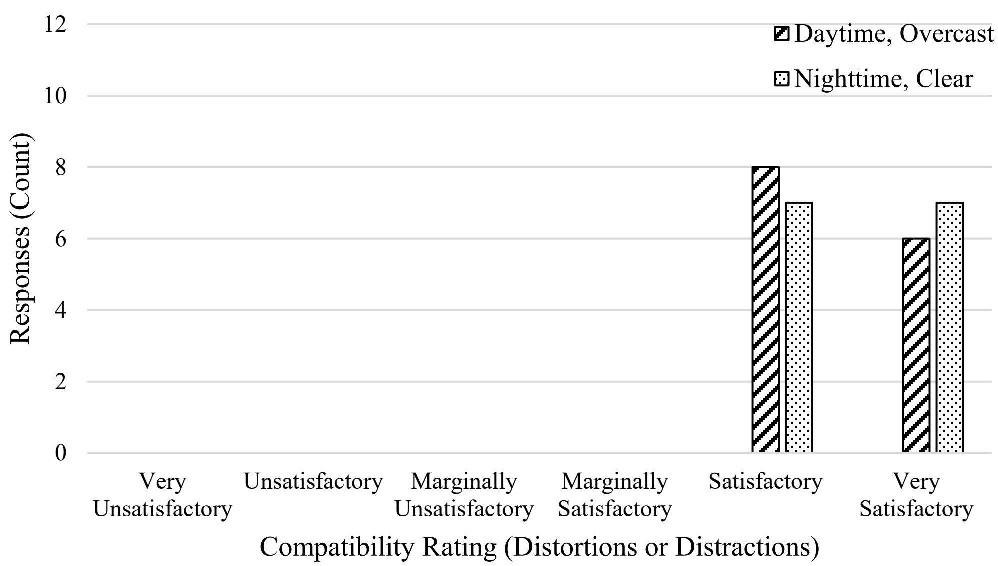


Figure 30

Question 13: Contrast and Visibility of the Scene Outside

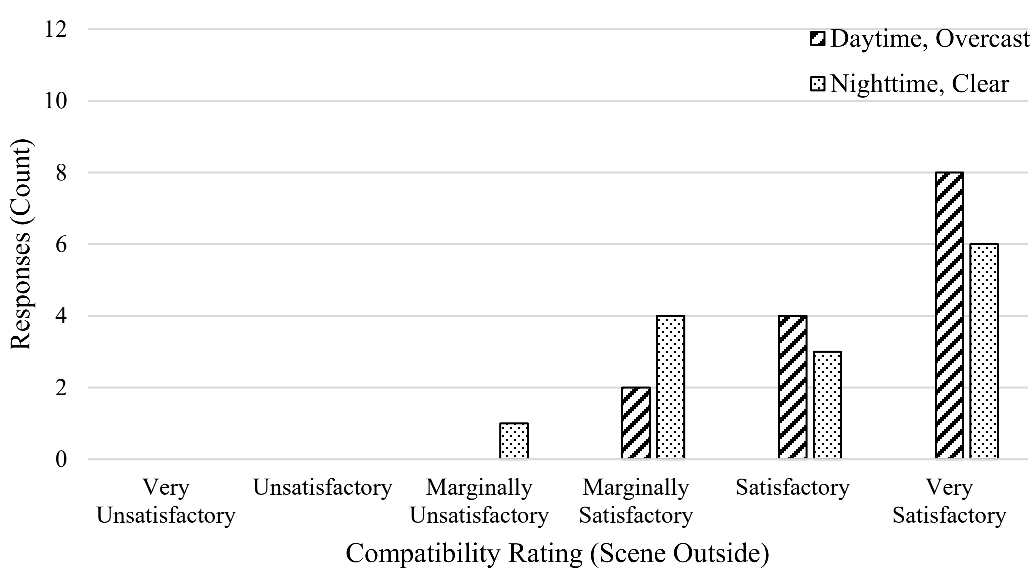


Table 13
Participant-provided Comments to Question 13

Environment	Comments for Less Than Satisfactory Response
Daytime, Overcast	It was easier to see outside with the glasses off
Daytime, Overcast	Glasses caused the horizon and clouds to appear discolored, but in equal proportions to where I was still able to tell differences between the two and safety wasn't compromised.
Nighttime, Clear	It was harder to see terrain outside at night
Nighttime, Clear	Outside scenery was a bit tougher to see at night with the glasses on than when off.
Nighttime, Clear	Tint does reduce the visibility of terrain at night slightly.
Nighttime, Clear	It seemed to me that the viewing outside at night was reduced with the glasses. I would. Not want to wear the glasses after departing the airfield environment. I would don them again 20-30 NM out from the field.
Nighttime, Clear	Harder to see the ground at night with the glasses on

Figure 31
Question 14: Please Rate Overall Visual Acuity (Ability to Read Small Text and Symbols) with LEP Glasses

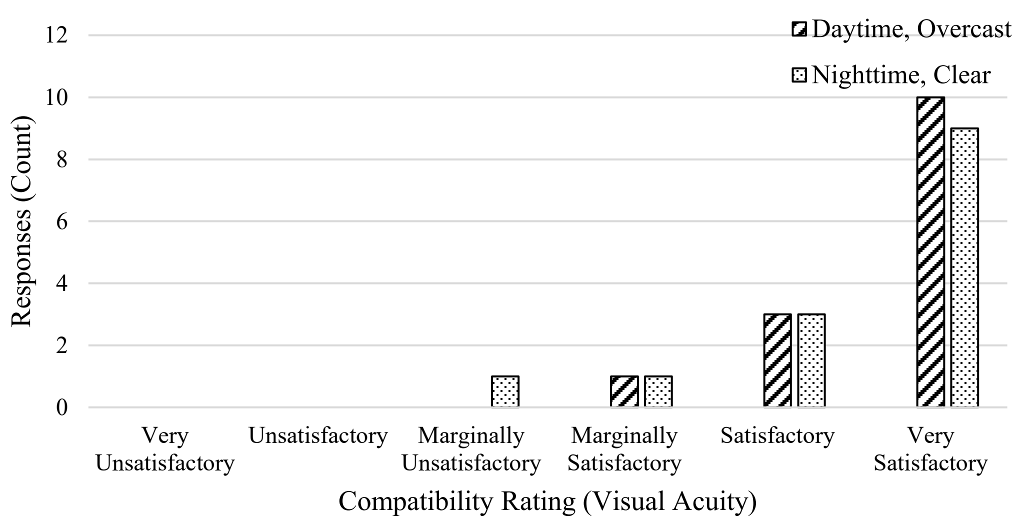


Table 14
Participant-provided Comments to Question 14

Environment	Comments for Less Than Satisfactory Response
Daytime, Overcast	Overall it was a little harder to see with the glasses on
Nighttime, Clear	If it wasn't lit up, it was harder to see words and symbols in the cockpit
Nighttime, Clear	Hard to read the checklist with the glasses on

Participants were generally satisfied with the CALI-2 LEP spectacles in terms of their physical comfort and ease of putting them on and taking them off (Figure 32, Figure 33, and Figure 34; see Table 15, Table 16, and Table 17 for specific comments).

Figure 32
Question 15: Rate the Overall Comfort of the LEP Glasses

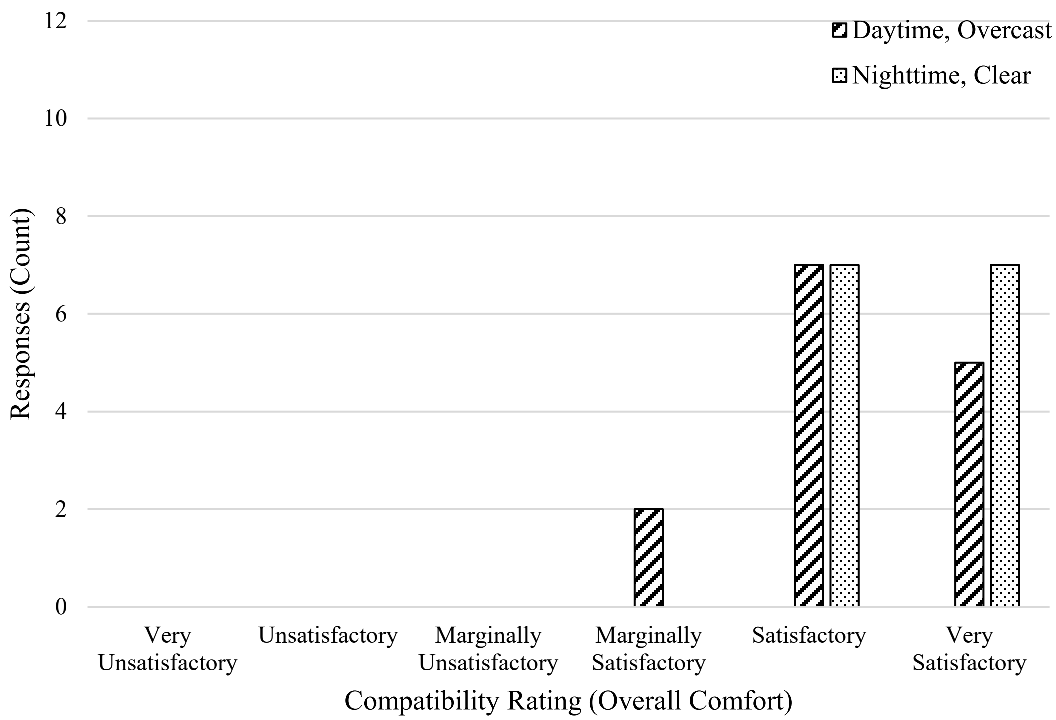


Table 15
Participant-provided Comments to Question 15

Environment	Comments for Less Than Satisfactory Response
Daytime, Overcast	Nose bridge was slightly low, headset caused pressure on the frames which pushed into the side of my head
Daytime, Overcast	I usually wear regular sunglasses so these might come as backup if I had them for my everyday flying

Figure 33
Question 16: Rate Ease of Putting On and Taking off the LEP Glasses

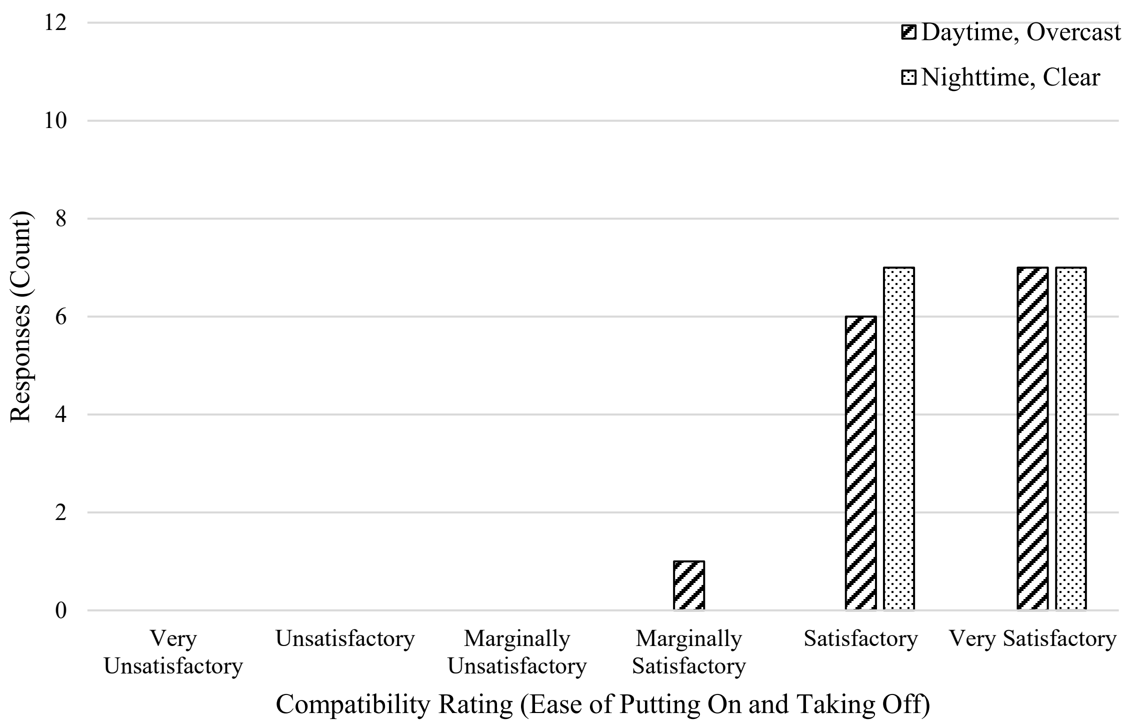


Table 16
Participant-provided Comments to Question 16

Environment	Comments for Less Than Satisfactory Response
Daytime, Overcast	Doesn’t smoothly fit under headset if removed and replaced during flight, a bit of adjustment of the headset was required to get them back on

Figure 34

Question 17: Rate the Ability of the LEP Glasses to Stay in Place while Worn During Normal Operations

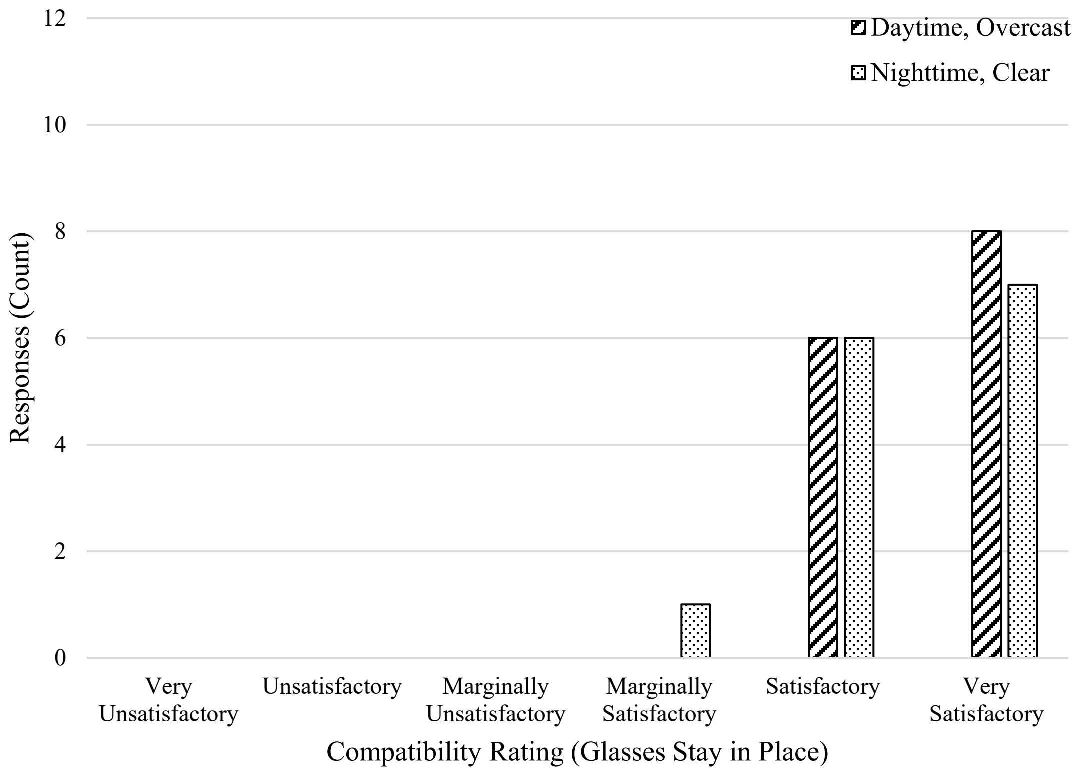


Table 17

Participant-provided Comments to Question 17

Environment	Comments for Less Than Satisfactory Response
Nighttime, Clear	They slid down a little but it wasn't too bad

Participants rated confidence for safe and effective operations when wearing the CALI-2 LEP spectacles as satisfactory (see Figure 35; see Table 18 for specific comments).

Figure 35

Question 18: Rate Your Confidence for Safe and Effective Operations with the LEP Glasses

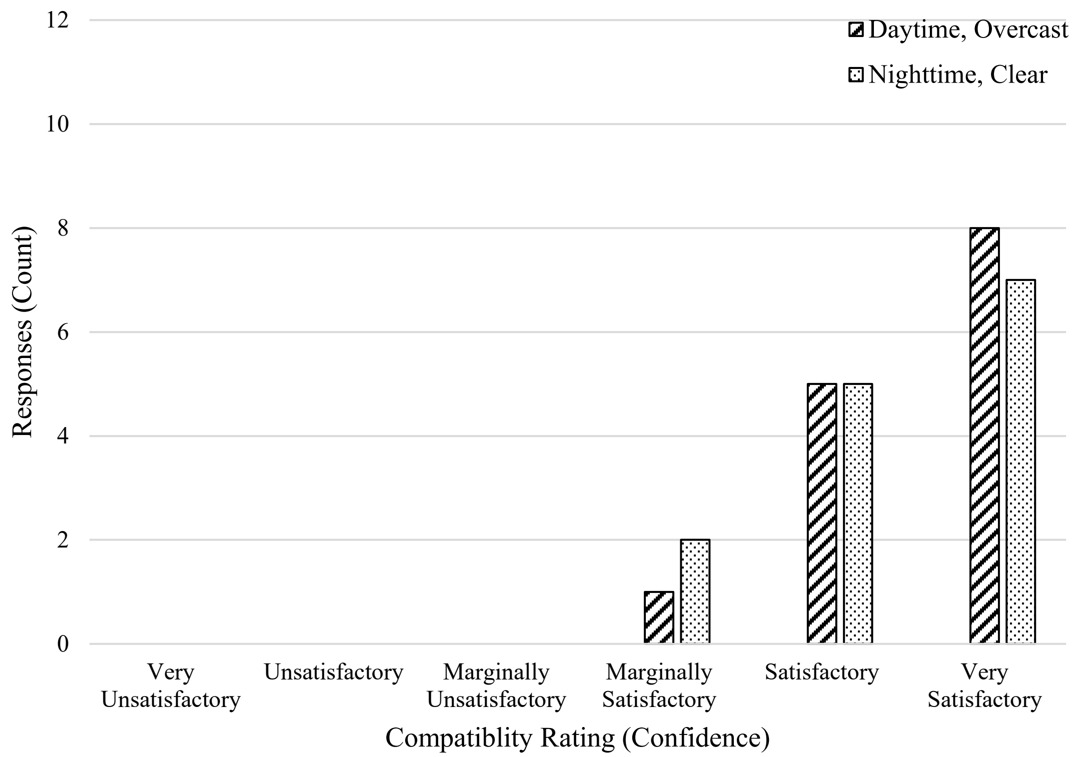


Table 18

Participant-provided Comments to Question 18

Environment	Comments for Less Than Satisfactory Response
Daytime, Overcast	Overall it was safe but I found it a little safer without the glasses
Nighttime, Clear	I felt safer without the glasses on
Nighttime, Clear	I think it depends on the person. I would be fine with them but I like not wearing them more. Safer without in my opinion

Post-Flight Interview Questions

Of the 14 participants, 13 stated they would feel comfortable wearing the CALI-2 LEP spectacles in a real aircraft when flying in similar conditions as those experienced during the study. One participant stated that the CALI-2 LEP spectacles made it appear as if the runway was narrower because the runway lights appeared enlarged; however, this participant was unsure whether the effect was caused by the CALI-2 LEP spectacles or by a simulator characteristic (see Appendix D for all post-flight comments).

Response to Alternator Breaker Malfunction

All but one of the participants responded to the alternator breaker malfunction by following the printed checklist (CheckMate, n.d.) and completed their response by resetting the Alternator No. 1 breaker switch. In the post-flight interview, the participant who did not follow the checklist explained that they recognized the alternator breaker malfunction and instead chose to address it after landing. They also noted that the simulator was equipped with redundant dual alternators, thus not impacting the aircraft's operation. These results suggest that pilots' ability to detect the alternator malfunction, follow a paper checklist procedure, and interact with dimly-lit physical switches in the flight deck was not impacted by use of the CALI-2 LEP spectacles.

Discussion

The purpose of this study was three-fold: to (a) evaluate the effects of wearing the CALI-2 LEP spectacles on pilot performance, (b) assess the degree to which CALI-2 LEP spectacles are compatible with flight deck displays, lights, controls, and out-the-window visual information, and (c) evaluate the usability of CALI-2 LEP spectacles for pilots in terms of form, fit, and function. To carry out this evaluation, participants completed a series of simulated flights either with or without the CALI-2 LEP spectacles and in a diverse range of flight environments (e.g., Daytime, Overcast and Nighttime, Clear). Lateral deviation during en-route flight and vertical deviation during the ILS approach in both environments were statistically equivalent. This suggests that wearing the CALI-2 LEP spectacles does not significantly impact the ability to follow a prescribed flight path.

It is important to note that several of these analyses did not reach significant equivalence. Furthermore, there was a significant difference found in lateral deviation from ILS localizer signal observed in the Daytime, Overcast environment, with greater FTE observed when participants wore the CALI-2 LEP spectacles versus when they did not. This finding is inconsistent with the findings from the remaining TOST analyses. This could be due to the smaller sample size for this analysis (n = 11) as a result of incomplete data. As such, it is possible that the statistical power was insufficient and that the observed effects are due to variability in the data rather than the experimental manipulation. Performance in the Daytime, Overcast environment was more likely to be impacted by this, as the 13 knot winds present in this scenario likely increased FTE and thus affected variability in the data when compared to the Nighttime, Clear environment, where there were no winds.

All pilots were able to detect the alternator malfunction, suggesting that the CALI-2 LEP spectacles do not hinder the pilots' ability to detect this malfunction; furthermore, the CALI-2 LEP spectacles did not hinder participants' ability to follow the checklist, correct the malfunction, and continue safely operating the aircraft. Given that this process involved interacting with dimly-lit information that was off axis from the primary FOV (i.e., overhead breaker panel, laminated paper checklist), the CALI-2 LEP spectacles likely allowed enough light to transmit through so as not to impede such processes. Pilots should be able to carry out these types of activities during flight in a real aircraft while wearing the CALI-2 LEP spectacles.

Taken together, these results suggest that pilots can wear CALI-2 spectacles in real general aviation aircraft without negative effects on performance. The results from the on-line probe data indicate that the perception and comprehension of color-coded alphanumeric information presented on the flight deck displays is preserved while wearing the CALI-2 LEP spectacles. The query task mimics the process of listening to audio communications over the headset, scanning relevant visual information in the flight deck, and repeating that information back over the radio. All participants were able to relay the queried information in an accurate and efficient manner. Additionally, query response time data suggest that there were no appreciable changes in the time it took to respond to the verbal queries while wearing the CALI-2 LEP spectacles.

Results of the Visual Compatibility Functional Test questionnaire suggest that pilots generally found CALI-2 spectacles satisfactory for use in a real aircraft. Pilots indicated that the CALI-2 LEP spectacles were generally “Satisfactory” or “Very Satisfactory” in all areas and in each environment. It is important to note that written feedback was only prompted when an item was rated as “Marginally Satisfactory” or below (i.e., Marginally Satisfactory, Marginally Unsatisfactory, Unsatisfactory, and Very Unsatisfactory). Therefore, this written feedback should be considered in context with the responses to the survey items. Common themes among the comments for less-than-satisfactory responses included difficulties seeing dimly-lit controls, non-illuminated text (e.g., paper checklists), and terrain during nighttime flight. Participants elaborated that they may be less likely to wear LEP spectacles during nighttime flight as the experience is akin to wearing sunglasses at night. Some pilots indicated that they would don the spectacles within 20-30 nm of the airfield environment. It is possible that participants may not wear LEP spectacles during a nighttime flight due to the reduced visibility of terrain and dimly-lit controls and may don them as a reaction to experiencing a laser strike.

Post-flight interview responses suggested that pilots would feel comfortable wearing the CALI-2 LEP spectacles in a real aircraft, that safety of flight would not be hindered, and that these characteristics may be consistent across daytime and nighttime flights. Moreover, follow-up discussions with the participants revealed that the sample was generally unaware of LEP technology and how it can be used to mitigate laser strikes. Participants were also generally not aware of any recommended practices on what the pilot should do in the event of a laser strike, or when LEP should be used. It is worth noting that these findings may not be generalizable to the civil aviation pilot population as a whole, such as Airline Transport Pilot population, due to the sample in this study being made up primarily of student pilots and general aviation pilots.

Limitations and Future Directions

The limitations of this study largely revolve around the limited sample size and compromises associated with flight simulation research. Although the participants were diverse in terms of their aviation-related experiences and use cases, the sample size ($n = 14$), and thus the statistical power, was small. This was compounded by instances where data could not be included in several of the FTE analyses. As such, future research that investigates impacts of LEP on FTE should include a larger sample of participants in order to increase the statistical power of those objective flight performance evaluations. Moreover, the sample was mainly General Aviation pilots, so any generalization of the findings to other pilot populations, such as Airline Transport Pilots, should be made with caution. Additionally, because the participants in this study possessed normal color vision, the findings of this study should not be generalized to pilots with a color vision deficiency. It is not known how the color vision shift caused by LEP spectacles would impact those pilots with color vision deficiencies.

An additional limitation of this research is related to the use of flight simulation, and the associated pitfalls of this method of evaluation compared to real flight tests. While flight simulators can reliably mimic many of the characteristics of real-world flight and are advantageous in terms of their consistency and data collection capability, they cannot replicate real-world flights; this is especially the case for out-the-window visual information, which cannot be reproduced accurately in a laboratory environment. Other factors include the lack of adjustable brightness of the simulated Garmin G1000 avionics suite and participants' limited ability to match the display's brightness with ambient lighting conditions. Furthermore, the out-the-window visual system does not replicate the real-world experience of out-the-window visuals in an aircraft, such as effects of glare, direct sunlight, and LED or incandescent airfield lighting. Future evaluations of CALI-2 LEP spectacles should include real-world flight testing to evaluate these elements.

Moving forward, future research efforts are needed to evaluate the impact of LEP spectacles on civil aviation flight. Future LEP research should take advantage of recent developments in LEP and laser eye dazzle simulations using virtual reality, in which a color appearance model can be applied to simulate the shift in color perception in tandem with laser dazzle simulation (Dykes et al., 2018; Freeman and Williamson, 2020). Additionally, there is a need for increased awareness among the pilot community regarding LEP technology, their potential effectiveness in mitigating the effects of laser strikes, and their compatibility with activities and duties associated with civil aviation flight. Finally, because individuals who possess a color vision deficiency are still able to obtain an Airman Medical Certificate if they pass an Operational Color Vision Test (see FAA, 2023a), it is recommended that future research investigate whether LEP spectacles are safe to use in flight by pilots with a color vision deficiency.

This research also has the potential to inform the development of recommended practices and standard operating procedures (SOPs) surrounding the use of LEP spectacles during flight.

As evidenced by the findings of this research, LEP spectacles use has a minimal impact on pilots' ability to carry out normal duties associated with flight in a general aviation aircraft; as such, LEP spectacles appear to present a minimal risk to flight safety. At the same time, pilots did report having difficulty seeing dimly-lit visual information, particularly terrain and dimly-lit controls at nighttime. This indicates that pilots may opt out of wearing LEP glasses during nighttime flight if the perceived risk of a laser event was low, and that donning LEP glasses may occur as a reaction to experiencing a laser strike rather than in advance of one. This reactionary process could cause pilots to divert attention away from other critical piloting duties to don the spectacles. This may jeopardize task management, particularly during high-workload phases of flight such as approach and landing. This is one example of an instance where a recommended practice or SOP surrounding the use of LEP glasses may be beneficial. Toward this end, future efforts should determine the use cases of LEP spectacles in context with other pilot duties and develop a risk profile that identifies the optimal time to don LEP spectacles so that other piloting duties are not neglected.

Taken together, the findings from this research indicate that LEP spectacles are a promising tool for reducing the risks associated with laser strikes, are likely compatible with the civil aviation flight deck and associated pilot duties, and there are opportunities to increase awareness of LEP technology among the pilot community and develop recommendations for their use during flight. Increased use and acceptance of LEP spectacles, combined with an established framework for their use, could potentially reduce in the impact of laser strikes in the National Airspace System (NAS).

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Appendix A. Demographics Questionnaire

Participants received the following Demographics Questionnaire in Qualtrics after they completed Informed Consent.

Demographic Questions	Response options
Age in years	Open Text
Gender	Male Female Prefer not to say
Please estimate your total flight hours	Open Text
Please estimate your flight hours in the past month	Open Text
What certificates/ratings/endorsements do you currently hold? [mark all that apply]	Student Pilot Certificate Sport Pilot Certificate Recreational Pilot Certificate Private Pilot Certificate Commercial Pilot Certificate Airline Transport Pilot Certificate Instrument Rating Multi-Engine Rating High-Performance Endorsement Complex Endorsement Tailwheel Endorsement Other (please define)
Have you flown a Piper Malibu before?	Yes No
Have you experienced a laser strike while flying?	Yes No
If yes, please estimate the number of laser strikes you have encountered	Open Text

Appendix B. Flight Plan Documents

Daytime, Overcast Flight Plan

PRIVACY ACT STATEMENT: This statement is provided pursuant to the Privacy Act of 1974, 5 USC § 552a: The authority for collecting this information is contained in 49 U.S.C. §§ 40113, 44702, 44703, 44709, and 14 C.F.R. Part 6 - [Part 61, 63, 65, or 67. The principal purpose for which the information is intended to be used is to allow you to submit your flight plan. Submission of the data is voluntary. Failure to provide all required information may result in you not being able to submit your flight plan. The information collected on this form will be included in a Privacy Act System of Records known as DOT/FAA 847, titled "Aviation Records on Individuals" and will be subject to the routine uses published in the System of Records Notice (SORN) for DOT/FAA 847 (see www.dot.gov/privacy/privacyactnotices).

Paperwork Reduction Act Statement: A federal agency may not conduct or sponsor, and a person is not required to respond to, nor shall a person be subject to a penalty for failure to comply with a collection of information subject to the requirements of the Paperwork Reduction Act unless that collection of information displays a current valid OMB Control Number. The OMB Control Number for this information collection is 2120-0026. Public reporting for this collection of information is estimated to be approximately 2.5 minutes per response, including the time for reviewing instructions,completing and reviewing the collection of information. All responses to this collection of information are mandatory per14 CFR Part 91. Comments concerning the accuracy of this burden and suggestions for reducing the burden should be directed to the FAA at: 800 Independence Ave. SW, Washington, DC 20591, Attn: Information Collection Clearance Officer, ASP-110.

Form Approved: OMB No. 2120-0026
Exp. 05/31/2017

FLIGHT PLAN
U.S. DEPARTMENT OF TRANSPORTATION
FEDERAL AVIATION ADMINISTRATION

(FAA USE ONLY) ☐ PILOT BRIEFING ☐ VNR ☐ STOPOVER | TIME STARTED | SPECIALIST INITIALS

1. TYPE	2. AIRCRAFT IDENTIFICATION	3. AIRCRAFT TYPE / SPECIAL EQUIPMENT	4. TRUE AIRSPEED	5. DEPARTURE POINT	6. DEPARTURE TIME PROPOSED (Z)	6. DEPARTURE TIME ACTUAL (Z)	7. CRUISING ALTITUDE
VFR ☐ / IFR ✓ / DVFR ☐	N1958P	Piper PA-46-350P	180 KTS	KBTV RWY 19	1200 EST	1200 EST	7000 ft

8. ROUTE OF FLIGHT
Takeoff KBTV RWY 19, climb heading 189 to 7000 ft
Fly heading 189 to 6B0
Turn left heading 074 to MPV
Turn left heading 299 to JANUD
Follow ILS procedure into KBTV RWY 33

9. DESTINATION (Name of airport and city)	10. EST. TIME ENROUTE HOURS	10. EST. TIME ENROUTE MINUTES	11. REMARKS
KBTV RWY 33	0	35	Visibility 2.0 SM Ceiling 350 ft AGL; overcast; unlimited visibility above 3000 ft; Winds heading 206 at 13 kt

12. FUEL ON BOARD HOURS	12. FUEL ON BOARD MINUTES	13. ALTERNATE AIRPORT(S)	14. PILOT'S NAME, ADDRESS & TELEPHONE NUMBER & AIRCRAFT HOME BASE	15. NUMBER ABOARD
6	30	N/A	N/A	1
			17. DESTINATION CONTACT/TELEPHONE (OPTIONAL): N/A	

16. COLOR OF AIRCRAFT
Blue

CIVIL AIRCRAFT PILOTS. FAR Part 91 requires you file an IFR flight plan to operate under instrument flight rules in controlled airspace. Failure to file could result in a civil penalty not to exceed $1,000 for each violation (Section 901 of the Federal Aviation Act of 1958, as amended). Filing of a VFR flight plan is recommended as a good operating practice. See also Part 99 for requirements concerning DVFR flight plans.

FAA Form 7233-1 (8-82)
Electronic Version (Adobe)

CLOSE VFR FLIGHT PLAN WITH ______________ FSS ON ARRIVAL

MILITARY STOPOVER (FAA USE ONLY)

TYPE	AIRCRAFT IDENTIFICATION	AIRCRAFT TYPE/SPECIAL EQUIPMENT	REMARKS
☐ IFR ☐ VFR			

DEPARTURE POINT	DESTINATION	ETA

TAS	DEP. PT	ETD	ALTITUDE	ROUTE OF FLIGHT	DESTINATION	ETE	REMARKS
KTS							
KTS							
KTS							
KTS							

REMARKS | INITIALS

FAA Form 7233-1 (8-82) Electronic Version (Adobe)

Nighttime, Clear Flight Plan

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FLIGHT PLAN
U.S. DEPARTMENT OF TRANSPORTATION
FEDERAL AVIATION ADMINISTRATION

(FAA USE ONLY) ☐ PILOT BRIEFING ☐ VNR ☐ STOPOVER | TIME STARTED | SPECIALIST INITIALS

1. TYPE	2. AIRCRAFT IDENTIFICATION	3. AIRCRAFT TYPE / SPECIAL EQUIPMENT	4. TRUE AIRSPEED	5. DEPARTURE POINT	6. DEPARTURE TIME PROPOSED (Z)	6. DEPARTURE TIME ACTUAL (Z)	7. CRUISING ALTITUDE
VFR ☐ / IFR ✓ / DVFR ☐	N1958P	Piper PA-46-350P	180 KTS	KBTV RWY 19	2300 EST	2300 EST	7000 ft

8. ROUTE OF FLIGHT
Takeoff KBTV RWY 19, climb heading 189 to 7000 ft
Fly heading 189 to 6B0
Turn left heading 074 to MPV
Turn left heading 299 to JANUD
Follow ILS procedure into KBTV RWY 33

9. DESTINATION (Name of airport and city)	10. EST. TIME ENROUTE HOURS	10. EST. TIME ENROUTE MINUTES	11. REMARKS
KBTV RWY 33	0	35	Unlimited ceiling and visibility; calm winds

12. FUEL ON BOARD HOURS	12. FUEL ON BOARD MINUTES	13. ALTERNATE AIRPORT(S)	14. PILOT'S NAME, ADDRESS & TELEPHONE NUMBER & AIRCRAFT HOME BASE	15. NUMBER ABOARD
6	30	N/A	N/A	1
			17. DESTINATION CONTACT/TELEPHONE (OPTIONAL): N/A	

16. COLOR OF AIRCRAFT: Blue

CIVIL AIRCRAFT PILOTS. FAR Part 91 requires you file an IFR flight plan to operate under instrument flight rules in controlled airspace. Failure to file could result in a civil penalty not to exceed $1,000 for each violation (Section 901 of the Federal Aviation Act of 1958, as amended). Filing of a VFR flight plan is recommended as a good operating practice. See also Part 99 for requirements concerning DVFR flight plans.

FAA Form 7233-1 (8-82)
Electronic Version (Adobe)

CLOSE VFR FLIGHT PLAN WITH ______________ FSS ON ARRIVAL

MILITARY STOPOVER (FAA USE ONLY)

TYPE	AIRCRAFT IDENTIFICATION	AIRCRAFT TYPE/SPECIAL EQUIPMENT	REMARKS
☐ IFR ☐ VFR			

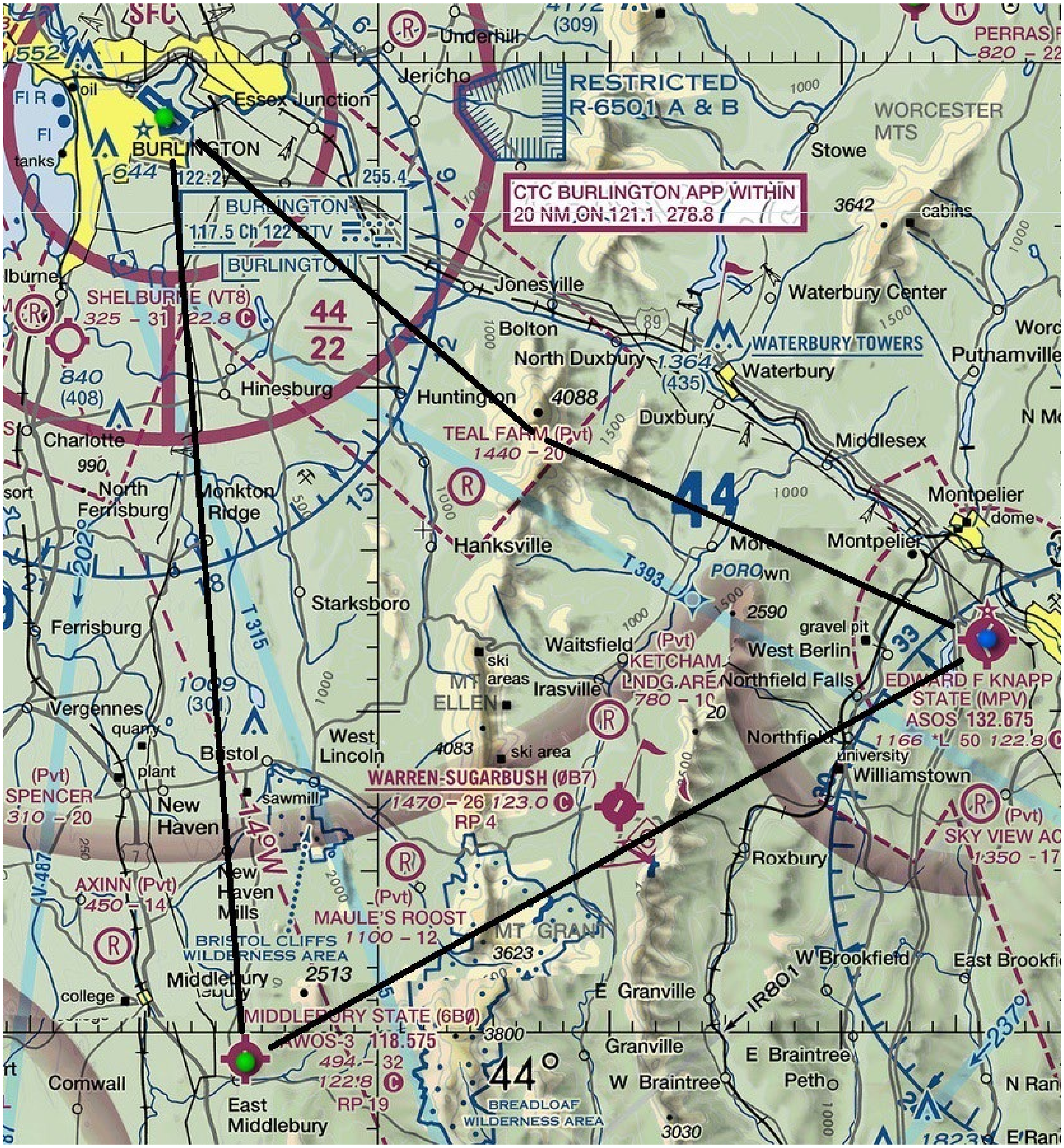
DEPARTURE POINT	DESTINATION	ETA

TAS	DEP. PT	ETD	ALTITUDE	ROUTE OF FLIGHT	DESTINATION	ETE	REMARKS
KTS							
KTS							
KTS							
KTS							

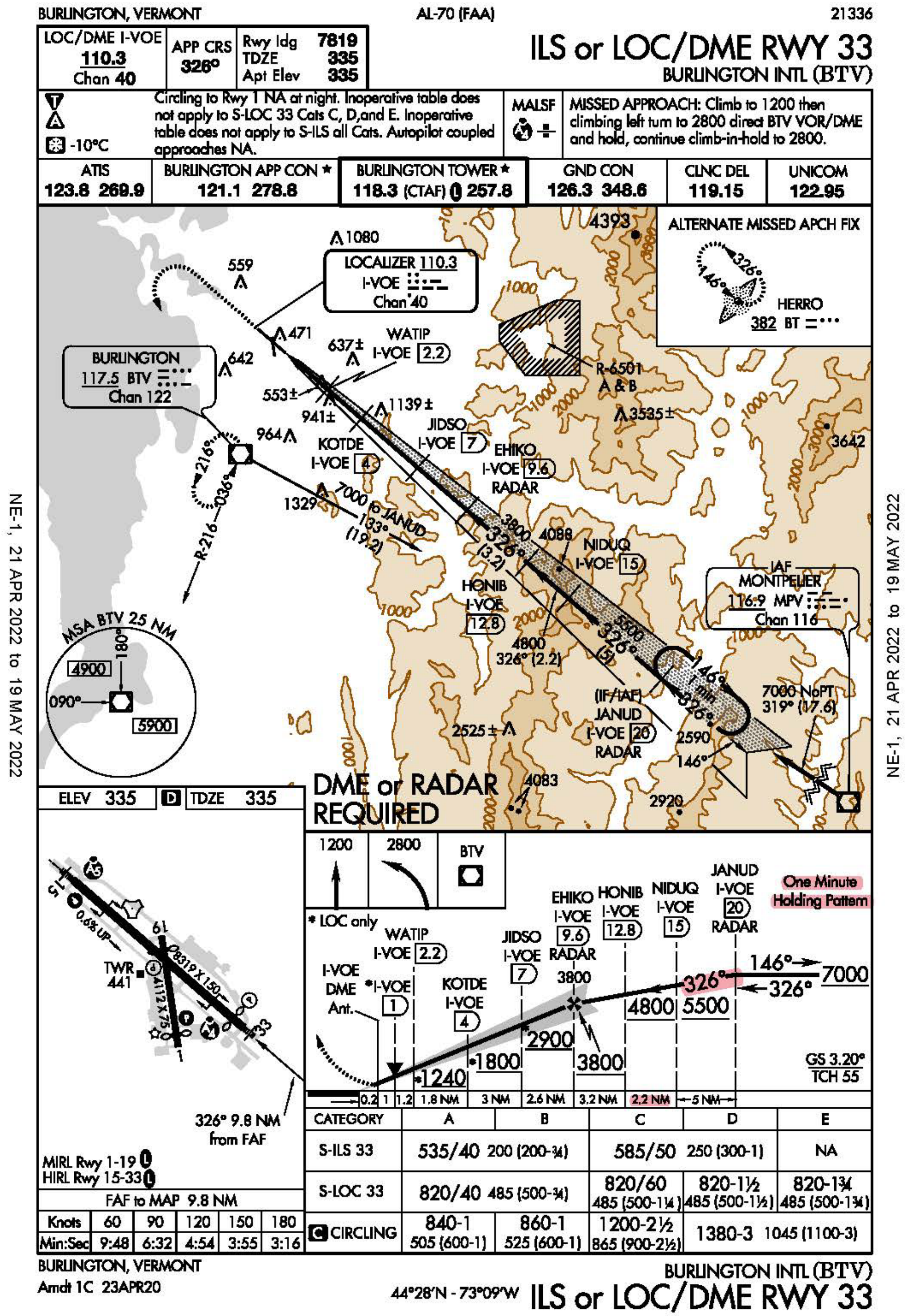
REMARKS | INITIALS

FAA Form 7233-1 (8-82) Electronic Version (Adobe)

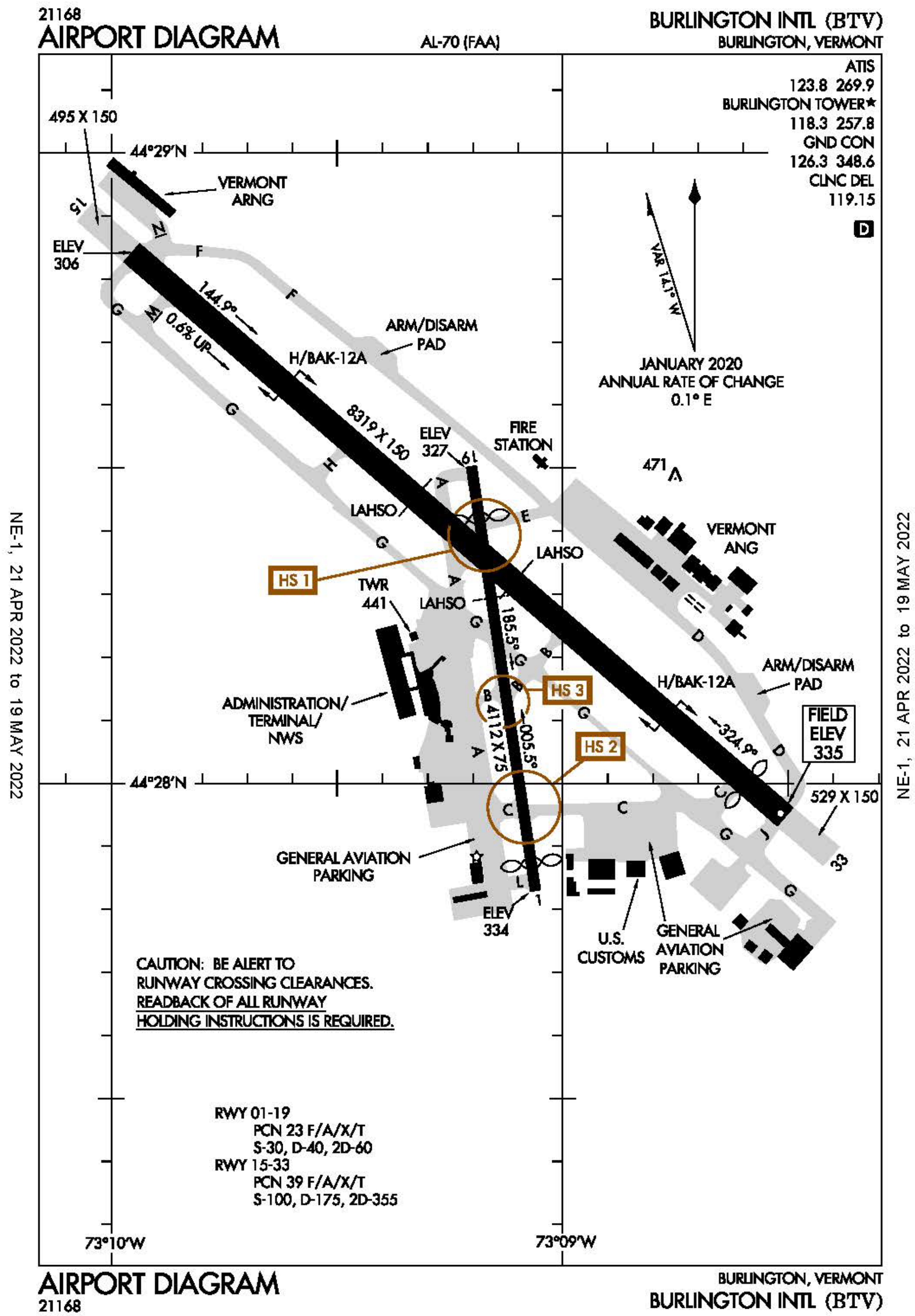
Flight Plan Map



KBTV ILS RWY 33 Approach Procedure



KBTV Airport Diagram



Piper PA-46-350P Checklist

The checklist used in this study is commercially available from CheckMate Aviation, Inc. See https://www.checkmateaviation.com

Appendix C.
Post-flight Questions

After completing the pair of daytime scenarios, the experimenter asked the participant:

- Do you feel like the glasses negatively impacted the flight in any way?
- All else being equal, would you feel comfortable wearing the glasses in a real aircraft in conditions such as these?
- Is there anything else about using the glasses that you'd like to mention?

After completing the pair of nighttime scenarios, the experimenter asked the participant:

- Did the glasses impact your ability to address the alternator malfunction?
- Do you feel like the glasses negatively impacted the flight in any way?
- All else being equal, would you feel comfortable wearing the glasses in a real aircraft in conditions such as these?
- Is there anything else about using the glasses that you'd like to mention?

The experimenter asked the participant an additional question after all of the scenarios:

- Comparing the daytime to nighttime flights, were the glasses any better or worse to use in one flight over the other? If so, why?

Participant comments are provided below (Table C1).

Table C1
Participant Comments to Post-flight Questions

Participant	Daytime, Overcast Environment	Nighttime, Clear Environment
P01	I do not like to wear glasses while flying and the darker tinted lenses may have a negative effect on vision. Smaller text was more difficult to read.	Out the window information was more difficult to see at night while wearing the glasses. It feels that glasses are safe to use in a real flight but does not like wearing tinted glasses and would not use. In cockpit screens were easier to read at night with glasses
P02	I did not think the glasses negatively affected flight performance. If the flight was in a real aircraft would feel comfortable with wearing the glasses.	No negative effect while wearing glasses. Glasses had no effect during failure condition. Compare night and day glasses were equally compatible.
P03	Participant stated glasses did not negatively affect the performance of the pilot. Participant stated they	I liked the glasses during the daytime conditions but at night made the screens darker and the glasses made me feel

Participant	Daytime, Overcast Environment	Nighttime, Clear Environment
	would feel comfortable wearing in a real aircraft. One negative to using the glasses during the day is not being able to wear sunglasses	slightly more tired or sleepy. The glasses had no effect on performance during the failure. Would feel comfortable using in a real aircraft
P04	The glasses did not have a positive or negative effect on flight performance. Would feel comfortable with using in a real aircraft.	The glasses did not have an effect on failure condition, comfortable to use in real aircraft. No difference between day and night conditions.
P05	In daytime, the glasses made the display seem like wearing a pair of light sunglasses. Viewing OTW with glasses on sharpened the horizon a little more. Would feel comfortable with using in a real aircraft during these conditions. During daytime no effect except the slight tint.	Feels like flying with sun glasses on at night. Nighttime visibility was reduced a little by wearing the glasses. Can tell a little difference of color but was still be able to read information. The yellow and red was easier to read without glasses but only a slight change. Would feel comfortable wearing the glasses during a normal operation in a real aircraft.
P06	Glasses did not affect flight performance. Would feel comfortable to use in a real aircraft. Noticed no difference between nighttime and daytime conditions while using the glasses.	I cannot even tell I am wearing glasses. No issue with warning light or failure conditions. would feel comfortable wearing glasses in a real aircraft under similar conditions
P07	Glasses did not affect the flight either way. Glasses did not affect pilot's ability to correct alt breaker issue. The cockpit displays are a little too bright. Unsure if wearing the glass at night in the mountains would be a good idea because it is usually much darker and makes it harder to see terrain, may not feel comfortable using during these conditions.	Glasses did not affected flight performance negative or positive. Glasses are better for use during daytime conditions. The tint might be too dark in instrument flight especially in mountainous terrain. Would feel more comfortable to use the glasses when not in a mountainous terrain. Would feel comfortable using in a real aircraft.
P08	Glasses did not have an effect on the flight performance, completely neutral. Was able to see and read all information with or without the glasses in daylight conditions.	Felt the glasses did not affect the overall flight positive or negative. However the glasses did make reading paper charts and breaker panel more difficult which required looking at the breaker panel twice to find the tripped breaker. Would feel comfortable wearing in a real aircraft

Participant	Daytime, Overcast Environment	Nighttime, Clear Environment
	Would feel comfortable using the glasses in a real aircraft.	in operational conditions similar to this simulated flight.
P09	The tinted lenses of the glasses increases visibility of magenta colored text. Would feel comfortable using in a real aircraft with all other conditions being the same.	The glasses made it easier on the eyes during nighttime because the in cock put displays were a little too bright. Glasses had not effect on correcting the failure condition. Between night and day, the tint would work better at night, the tint is not dark enough for day. All else equal, would feel comfortable using these glasses during a real flight.
P10	The glasses did not affect the flight either negative or positive. Would feel comfortable using in a real aircraft	The glasses positively affected the flight because the displays were a little brighter than in a real aircraft and the glasses helped. No difference between the day and night conditions. would be comfortable using the glasses in a real aircraft during similar conditions
P11	The glasses did not affect the flight in either a positive or negative way. Glasses might be better during the day because they reduce glare and may work similar to sunglasses. Would feel comfortable using in a real aircraft	Glasses had no difference in the operation of the aircraft. Glasses had no effect on the alternator failure. Would feel comfortable using LEPs in a real aircraft
P12	Liked the glasses more during the day than at night, believe the glasses helped with glare during day light, especially in low visibility conditions. Glasses are very comfortable and even forget they were on. Would wear the glasses during all phases of flight in the day but would remove once at altitude at night.	Do not think the glasses negatively affected pilot's performance; however, they did make it slightly more difficult to see out the window during a night flight. Would probably not wear the glasses during all phases of flight and would only wear them when at lower altitudes or near airports when a laser strike is more likely.

Participant	Daytime, Overcast Environment	Nighttime, Clear Environment
P13	One negative to using the LEP glasses is the slight color shift caused by the lens color as it slightly shifted the interment lighting, especially the color blue. Once the color shift became familiar it was not a major issue.	The glasses made the runway lights appear larger and more blurry, making the perception of the runway narrower. Not sure if the runway lights were caused by the glasses or if it was a product of the simulator. Would not feel comfortable if the runway lights were caused by the glasses. The glasses also caused a noticeable color shift. On the initial takeoff while wearing the glasses noticed the takeoff slope was yellow, but then realized it was the glasses and the actual display was white.
P14	Glasses did not have a negative affect while flying or reading checklists during the day. Would feel comfortable using in a real aircraft.	The LEP glasses made it more difficult to read the paper material and to see outside during night flights. However, would feel comfortable using in a real aircraft.

Appendix D.
Visual Compatibility Functional Test

The Visual Compatibility Functional Test was provided courtesy of the AFRL.

Visual Compatibility Functional Test
CALI-2 Questionnaire

Participant ID: ____ Date: ____

Experimental Condition		
		Daytime
		Nighttime

Do you require scripted lenses for vision correction?	YES		NO	
Did you wear contact lenses during this evaluation?	YES		NO	

Please rate the questions on a scale from 1 to 6 as shown in the diagram

1	2	3	4	5	6
Very Unsatisfactory	Unsatisfactory	Marginally Unsatisfactory	Marginally Satisfactory	Satisfactory	Very Satisfactory

	Provide a rating for each of the items below in terms of readability and color or brightness changes that might affect visual performance to the extent as to interfere with mission completion	Spectacle RATING 1-6
	If you rate an item as 1, 2, 3 or 4, please provide an explanation in the Comments section	
	General Assessment Questions	
1	Compatibility with color displays (i.e. smart phone, tablet, computer, etc.)	
2	Compatibility with monochromatic displays[1]	
3	Compatibility with Warning, Caution and Advisory Lights (Reds, Greens, Yellows)	
4	Color, contrast and visibility of surfaces. Includes switches, rotary dials, printed words and symbols as well as kneeboard maps and other materials	
5	Color, contrast and visibility of terrain colors and geographical features (not a display)	
6	Performance of normal duties are not hindered nor impaired to the extent as to interfere with safety or mission completion.	
7	Rate personal safety while utilizing CALI-2. Note any hazards.	
8	Rate any anticipated impact on detection, recognition, identification, and tracking of targets to the extent as to interfere with safety or mission completion.	
9	Field of View, any interference or obstruction with the LEP spectacle frame or lenses	
10	Field of View, any interference or obstruction with the visual line of sight to any instrument or display that is critical to normal flight tasks	
11	Overall transmission of the LEP in terms of visibility (too bright? too dark?)	
12	Any distortions or distractions (reflections) that hinder or impair visual performance to the extent as to interfere with safety or flight completion	
13	Contrast and visibility of the scene outside	
14	Please rate your overall visual acuity (ability to read small text and symbols) with the CALI-2 device	
	Field of View, Fit, and Comfort	
15	The overall comfort of the CALI-2 device	
16	The ease of donning and doffing the CALI-2 device	
17	The ability of the CALI-2 device to stay in place while worn during normal operations	
18	Your confidence for safe and effective operation with the CALI-2 device	
	COMMENTS	

Appendix E.
TOST Procedure

Non-significant *p*-values are traditionally interpreted as having a "null" effect (i.e., no significant effect of the independent variable was found or no significant difference was observed). Traditional hypothesis testing typically sets the alternative hypothesis as identifying a significant difference between groups (between-subjects designs) or conditions (within-subject designs), and the null hypothesis as failing to identify a significant difference. This method does not evaluate the hypothesis that conditions are equal or "significantly equivalent" (Hauck and Anderson, 1984).

Significant equivalence is frequently discussed in the scientific literature and in aviation safety research. For example, Schuirmann (1987) compared a new medical drug to the efficacy of one already approved and on the market. Beringer and Fercho (2020) and Williams et al. (2021) provided statistical evidence that a new safety device or safety philosophy is equally as safe as current practices.

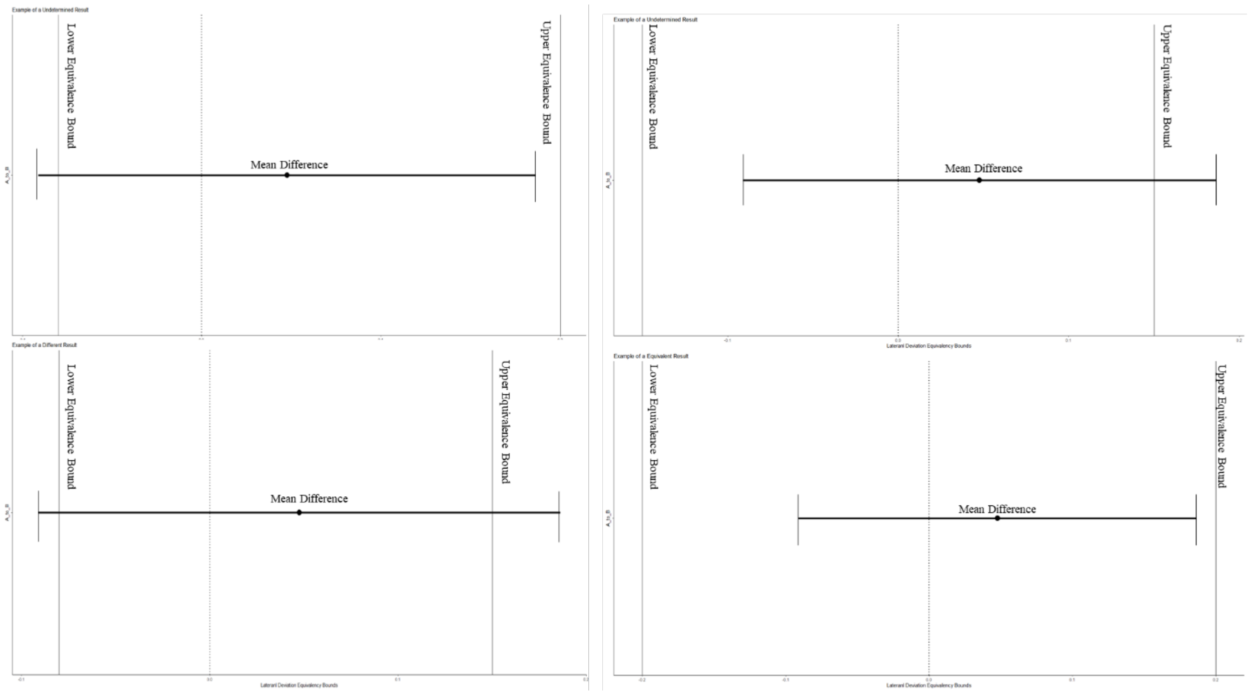
The study sought to determine whether safety levels associated with wearing and not wearing the CALI-2 Spectacles were equivalent. In this context, a non-significant result of the traditional parametric statistics would provide evidence that no difference can be found between wearing and not wearing the CALI-2 spectacles. To provide statistical support that piloting performance when wearing CALI-2 spectacles is *equivalent* to performance when not wearing them, the TOST procedure (Lakens, 2017) was conducted with pilot performance variables (e.g., FTE).

There are three types of possible outcomes for the TOST analysis, including: *undetermined*,[1] *statistically different*, or *statistically equivalent*. Outcomes are considered *undetermined* if the traditional hypothesis-testing *t*-test is non-significant but either of the additional TOST *t*-tests are also non-significant (i.e., sample confident intervals are outside the lower or upper boundaries). Outcomes are considered *statistically different* if the traditional hypothesis-testing *t*-test is significant and if the confidence-interval *t*-tests are non-significant and beyond upper and lower boundaries (for more information about setting boundaries, see Lakens, 2013, 2017; Seaman and Serlin, 1998). Lastly, outcomes are considered *statistically equivalent* if the traditional hypothesis-testing *t*-test is non-significant and the TOST results are significant (see Figure E1 for illustrations of the possible outcomes).

[1] Two statistical results of the TOST, confidence interval is statistically outside of the upper or lower bounds the results are considered *undetermined*.

Figure E1

Four Outcomes of the TOST Method



Note. Mean difference is denoted by circle in the middle of the horizontal line that represents 95% confidence interval. Center vertical line represents 0, outer vertical line represent upper and lower boundaries of equivalency test with large effect size assumption, The two upper panels show examples of undetermined results, the bottom left panel shows an example of a significant difference result, and the bottom right panel shows an example of a significantly equivalent result (the graphs represented above are sample data and not results of the current study but only to provide an example of the possible outcomes and interpretations of the graphs.

It is important to set objective boundaries before reviewing the study data to ensure objective review of the research. These boundaries are the criteria the conditions are compared. Due to the lack of literature available for objective bounds-setting in TOST, the upper and lower bounds were set using the largest effect size of interest. For the current research, the SEOSI was determined to consider a large effect size, for a Cohen's *d* of 0.8 (Cohen, 1988; Lakens, 2013, 2017).