APPENDIX A – LITERATURE REVIEW

ASSURE A46 – Validation of Visual Operation Standards for Small UAS (sUAS): Literature Review

October 4, 2021

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TECHNICAL REPORT DOCUMENTATION PAGE

1. Report No. A11L.UAS.88–A46-001	**2. Government Accession No.**	**3. Recipient's Catalog No.**
4. Title and Subtitle Validation of Visual Operation Standards for Small UAS (sUAS): Literature Review		**5. Report Date** October 4, 2021 **6. Performing Organization Code**
7. Author(s) Harsh Shah, Tom Haritos, Ph.D., Henry Cathey, Ph.D., Alan Martinez, Ph.D., Katie Silas, and Justin MacDonald, Ph.D.		**8. Performing Organization Report No.**
9. Performing Organization Name and Address National Institute for Aviation Research Wichita State University 1845 Fairmount Wichita, KS 67260-0193		**10. Work Unit No.** **11. Contract or Grant No.**
12. Sponsoring Agency Name and Address U.S. Department of Transportation Federal Aviation Administration Office of Aviation Research Washington, DC 20591		**13. Type of Report and Period Covered** Final – October 2021 **14. Sponsoring Agency Code** 5401
15. Supplementary Notes		

16. Abstract

The Alliance for System Safety of UAS through Research Excellence (ASSURE) A46 research task "A11L.UAS.88: Validation of Visual Operation Standards for Small UAS (sUAS)" aims to address gaps in knowledge to quantify VO/RP performance, identify potential visual detection limitations, and inform safety training standards for Visual Line Of Sight (VLOS) and Extended Visual Line Of Sight (EVLOS) operations. To address the gaps in knowledge and key concerns regarding VO/RP capabilities as they relate to 14 CFR Part 107 operations, the ASSURE A46 research team, consisting of Kansas State University (KSU), Wichita State University (WSU), New Mexico State University (NMSU) and Mississippi State University (MSU), conducted a literature review to identify the current state of research on VO/RP visual acquisition and avoidance of potential collision hazards. The information captured in this literature review will be used for planning simulations, tests, demonstrations, and/or analysis needed to assess VO/RP performance and validate related standards. The resulting output of the A46 research task will: (1) help the FAA and industry consensus standards bodies, such as American Society for Testing and Materials (ASTM), to better understand the safety performance and challenges associated with VO/RP performance in VLOS and EVLOS operations, and (2) potentially inform recommendations for future regulatory updates to 14 CFR Part 107.

17. Key Words	**18. Distribution Statement**
Visual Operation, small UAS, Visual Observer, Remote Pilot, Visual Detection, Extended Visual Line Of Sight (EVLOS)	No restrictions. This document is available through ASSURE.

19. Security Classification (of this report)	**20. Security Classification (of this page)**	**21. No. of Pages**	**22. Price**
Unclassified	Unclassified	101	0

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

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LIST OF ACRONYMS

AGL	Above Ground Level
ASSURE	Alliance for System Safety of UAS through Research Excellence
ASTM	American Society for Testing and Materials
ATC	Air Traffic Control
ATS	Air Traffic Services
BVLOS	Beyond Visual Line of Sight
BVLOS-G	Beyond Visual Line of Sight-Goggles
BVLOS-M	Beyond Visual Line of Sight-Monitor
CFR	Code of Federal Regulations
COA	Certificates of Waiver or Authorization
CRM	Crew Resource Management
DAA	Detect and Avoid
DPY	Definitely or Probably Yes
DY	Definitely Yes
EVLOS	Extended Visual Line of Sight
FAA	Federal Aviation Administration
FAR	Federal Aviation Requirements
GPS	Global Positioning System
KSU	Kansas State University
LOS	Line of Sight
MC	Mission Commanders
NAS	National Airspace System
NASA	National Aeronautics and Space Administration
NMSU	New Mexico State University
NTSB	National Transportation Safety Board
PF	Pilot Flying
PIC	Pilot in Command
PM	Pilot Monitoring
PSURT	Public Safety Unmanned Response Team
RP	Remote Pilot
RPIC	Remote Pilot in Command
SAR	Search and Rescue

SSO	Spatial Standard Observer
sUA	small Unmanned Aircraft
sUAS	small Unmanned Aircraft System
TCAS	Traffic Alert and Collision Avoidance System
UA	Unmanned Aircraft
UAF	University of Alaska Fairbanks
UAS	Unmanned Aircraft System
UND	University of North Dakota
V/STOL	Vertical/Standard Take-Off and Landing
VFR	Visual Flight Rules
VLOS	Visual Line of Sight
VMC	Visual Meteorological Conditions
VO	Visual Observer
VTOL	Vertical Take-Off and Landing
WSU	Wichita State University

EXECUTIVE SUMMARY

A major challenge associated with the integration of Unmanned Aircraft System (UAS) operations within the National Airspace System (NAS) is the ability to comply with 14 Code of Federal Regulations (CFR) § 91.111, 91.113, and 91.115, which require UAS operations ensure collision avoidance with other traffic in the airspace. The current regulations (14 CFR § 107.31) allow for a Visual Observer (VO) to assist the Remote Pilot (RP) in providing an additional set of eyes to scan the airspace around the small Unmanned Aircraft (sUA) for air traffic. The VOs are responsible for maintaining compliance with 14 CFR § 91.111, 91.113, and 91.115 regulations.

The Alliance for System Safety of UAS through Research Excellence (ASSURE) A46 research task "A11L.UAS.88: Validation of Visual Operation Standards for Small UAS (sUAS)" aims to address gaps in knowledge to quantify VO/RP performance, identify potential visual detection limitations, and inform safety training standards for Visual Line Of Sight (VLOS) and Extended Visual Line Of Sight (EVLOS) operations.

To address the gaps in knowledge and key concerns regarding VO/RP capabilities as they relate to Part 107 operations, the ASSURE A46 research team, consisting of Kansas State University (KSU), Wichita State University (WSU), New Mexico State University (NMSU) and Mississippi State University (MSU), conducted a literature review to identify the current state of research on VO/RP visual acquisition and avoidance of potential collision hazards.

For this literature review, the A46 research team reviewed the limitations of the human visual system and human visual performance models. The team identified the most common type of visual illusions that VO/RPs could experience. The team also identified the role of lighting systems and paint schemes that could enhance the aircraft visual conspicuity. There are only a limited number of experiments, publicly available, that have been performed to assess the role of VO/RPs in visual detection of sUAS. The A46 research team identified the key findings and limitations of these experiments which are laid out in the conclusion section of this report. The team also identified contradictions among the findings of these experiments.

While there are no standardized training requirements for VOs, many UAS Flight Test sites have their own training guidelines. The A46 research team investigated the current VO/RP training paradigm and briefly discussed extension of the VO/RP training paradigm towards EVLOS operations. The team also identified several training topics that could be critical in establishing safe VO/RP performance during EVLOS operations.

The research team will utilize the information captured in this literature review for planning simulations, tests, demonstrations, and/or analysis needed to assess VO/RP performance and validate related standards. The resulting output of the A46 research task will: (1) help the FAA and industry consensus standards bodies, such as American Society for Testing and Materials (ASTM), to better understand the safety performance and challenges associated with VO/RP performance in VLOS and EVLOS operations, and (2) inform recommendations for future regulatory updates to Part 107.

1 INTRODUCTION AND BACKGROUND

The emergence of copious small Unmanned Aircraft System (sUAS) operations in the last decade, for both hobby and commercial purposes, has highlighted the need for further research and reforms in the current regulations. The current regulations (14 Code of Federal Regulations (CFR) Part 107) require sUAS operations to be within Visual Line of Sight (VLOS) of the Remote Pilot (RP). Due to these requirements, the RP must always maintain visual contact with the sUAS without any visual aids except for corrective lenses. Beyond Visual Line of Sight (BVLOS) operations are regularly used in the military and are on the rise for commercial operations (Dunn, Molesworth, Koo, & Lodewijks, 2020). Operators can request waivers for BVLOS operations.

A major challenge associated with the integration of Unmanned Aircraft System (UAS) operations within the National Airspace System (NAS) is the ability to comply with 14 CFR § 91.111, 91.113, and 91.115, which require UAS operations ensure collision avoidance with other traffic in the airspace (Dolgov, 2016).

The current regulations (14 CFR § 107.31) allow for a Visual Observer (VO) to assist the RP in maintaining safety, providing an additional set of eyes to scan the airspace around the small Unmanned Aircraft (sUA) for air traffic that may pose a collision risk. The RP has the final authority in the operation of the aircraft, including commanding maneuvers, flight planning, and ensuring the overall safety of flight. Both the VO and RP serve critical roles in the operation of sUAS.

The Federal Aviation Administration (FAA) has identified the following concerns regarding VO capabilities as they relate to Part 107:

- 14 CFR § 107.29, it is unknown how well VOs/RPs can avoid manned aircraft at night (e.g., a waiver to § 107.29) or during periods of civil twilight when the sUAS is equipped with anti-collision lighting visible for at least three statute miles (sm). It is unknown what factors VOs/RPs may encounter and how this may impact future training standards.
- 14 CFR § 107.31, it is unknown how well VOs/RPs can ascertain the position of an sUA in terms of location, attitude, altitude, and direction of flight using vision unaided by any device other than corrective lenses. It is also unknown how well RPs can use visual reference information to detect and avoid other air traffic and/or collision hazards.
- 14 CFR § 107.33, it is unknown what challenges may arise from VO and RP communications when a VO relays information to an RP about a perceived intruder aircraft or other potential collision hazards.
- 14 CFR § 107.37, it is unknown how well VOs/RPs can give way to conflicting aircraft and avoid the creation of a collision hazard.

Recent experience with sUAS flight tests and a theoretical assessment of visual limitations have revealed potential challenges and optical illusions that may arise for VO/RP Line Of Sight (LOS) operations. The purpose of this research is to assess the performance ability of VOs/RPs to meet the above Part 107 requirements, understand the various challenges that could be encountered during operations to create VO/RP training recommendations for visual line of sight operations, and to provide information for potential future updates to Part 107 regulations.

The A46 team conducted this literature review that explores human factors considerations for the VO role for sUAS flight operations. It includes (1) a review of existing studies on aircraft lighting systems and paint schemes that make the aircraft more conspicuous (2) a review of the current VO/RP training paradigm (3) an investigation of the roles that the VO and the RP have in testing Detect and Avoid (DAA) systems. In addition the researchers make some comments on the extension of the role of the VO/RP training paradigm towards Extended Visual Line of Sight (EVLOS).

The research team also explored the current state of research on the see and avoid principle. This principle, which relies on the visual detection capabilities of manned aircraft pilots to avoid a potential collision with other traffic, has been studied in aviation for a few decades. There have only been a handful of experimental studies, publicly available, that have attempted to quantify the see and avoid principle (Watson, Ramirez, & Salud, 2009). Most of these experiments were conducted more than 20 years ago, at a time when UAS had not even been conceptualized. The research team included these experiments in the literature review since (1) some of these experiments are used as benchmark to assess human visual performance models (2) these experiments provide additional data points to relate human visual detection with aircraft characteristics such as size, distance, and contrast with the background (3) certain visual scanning strategies used by observers in these experiments might be beneficial in UAS visual detection.

This literature review serves as a foundation element for Alliance for System Safety of UAS through Research Excellence (ASSURE) A46: Validation of Visual Operation Standards for Small Unmanned Aircraft Systems (sUAS). Follow-on tasks will build upon this literature review to develop test plans and case studies to expand upon the current body of knowledge surrounding VO performance, training requirements, and human factors considerations.

2 LITERATURE REVIEW

This literature review is divided into the following five main sections:

- Human Factors Related to VO/RP Performance
- Factors Related to Aircraft Visual Conspicuity
- The Current VO/RP Training Paradigm
- The Role of VO/RP in Testing of DAA
- Extension of VO/RP Training Paradigm Towards EVLOS Operations

2.1 Human Factors Related to VO/RP Task Performance

Given the reliance of the RP and VO on instrumentation, sensory perception, environmental cues, and decision-making processes to ensure the safety of flight, an exploration of human factors considerations for VO and RP task performance is warranted. This section explores literature relating to human visual system limits, human visual performance model(s), topics relating to spatial disorientation and visual illusions, visual observer accuracy, non-visual detection, and team performance.

2.1.1 Human Visual System Limits

Exploring the limitations of human vision enables further understanding of key constraints for VO and RP performance measures. This is especially true as both the VO and RP rely heavily on their vision to safely fulfill their crew roles.

Graham (1989) notes that the ability of the eye significantly reduces by half a degree from the fovea (50% at a distance of 30 ft) (Bartlett et al., 1965). The author also notes that the eye can achieve its maximum detection capabilities if it takes 540 seconds to search a 15° to 30° field of view. Graham (1989) references Edwards and Harris (1972) and Graham (1974) to mention that theoretical and experimental work proved that traffic alerts are less feasible without bearing information. Graham (1989) states that although there is a detection probability improvement with a bearing accuracy of 30°, a fraction of undetected targets are still left. Graham (1989) references the work of Edwards and Harris (1972) which estimated a fixated target (Cessna 180 flying head-on with a closing speed of 320 kts) was detected 50% of the time at 23 seconds (pilot alerted at 3 nm). When the field of view was limited to 15° by 60°, the 50% detection point was at 10 seconds. The 50% detection point was at 12 seconds for a smaller field of view of 15° by 30°, and at 14 seconds for a further smaller field view of limited to 15° by 15°.

Hobbs (1991) provides a list of factors that affect the human visual system limitations and categorizes the human visual system limits into five different categories. According to Hobbs (1991), these categories are blind spot, threshold for acuity, accommodation, empty field myopia, and focal traps. These categories are summarized as follows:

- Blind Spot

  The blind spot is where the optic nerve exits the eyeball. This spot covers 7.5° of vertical visual angle and 5° horizontal visual angle (Westheimer, 1986). The blind spot is able to obscure a small plane as the obscured area can reach to approximately 18 m in diameter at a distance of 200 m. Blind spot problems arise when the view from one eye is obstructed, preventing binocular vision from compensating for the problem.

- Threshold for Acuity

  Visual acuity becomes a factor when an approaching aircraft is too small to be seen. Acuity can be reduced due to vibration, fatigue, hypoxia, and certain types of sunglasses (Dully, 1990; Welford, 1976; Yoder & Moser, 1976). Attempts were made to specify the size of the retinal image of an aircraft. However, since visual acuity varies dramatically across the retina, the author notes that it was not possible to determine the target size. An aircraft is first noticed by peripheral vision in most cases (Hobbs, 1991).

- Accommodation

  Accommodation is the eye focusing on an object through muscle movement. A young person requires one second to accommodate (Westheimer, 1986), and the average pilot takes a few seconds to accommodate distant objects. The speed and degree of accommodation are affected by age and fatigue (Hobbs, 1991).

- Empty Field Myopia

Empty field myopia is the effect where the eye focuses at too a short distance in the absence of visual cues. The eye focuses at a distance of 50 cm in the dark and focuses at a distance of 56 cm in an empty field (Roscoe & Hull, 1982). An effort is required to focus at greater distances, especially during absence of visual cues since the natural focus point (dark focus) is at a distance of 50 cm (Hobbs, 1991).

- Focal Traps

  Focal traps are caused by the Mandelbaum effect phenomenon, which occurs when visibility is poor, such as in dark conditions, the eye tends to relax and focus on objects close to the observer (Hobbs, 1991).

Hobbs (1991) also provides a list of factors that affect the human visual system limits in terms of psychological limitations. Hobbs (1991) categorizes the psychological limitations into three categories: alerted search versus unalerted search, visual field narrowing, and cockpit workload and visual field narrowing.

- Alerted Search versus Unalerted Search

  A traffic search is more successful when provided with traffic information compared to when traffic information is absent. This is because the pilot knows where to look for traffic (Edwards & Harris, 1972). Traffic alerts from Air Traffic Services (ATS) are found to be equally effective as the traffic alerts from a radio listening watch. The traffic alerts from ATS are found to increase the traffic search effectiveness by 8-folds compared to search in the absence of traffic alerts (Andrews, 1977, 1984; J. W. Andrews, 1991).

- Visual Field Narrowing

  Fatigue, stress or a larger cockpit workload is likely to induce tunnel vision even in situationally aware pilots and degrade their field of view (Hobbs, 1991). Hypoxic conditions and adverse thermal conditions are also observed to cause visual field narrowing (Leibowitz, 1973).

- Cockpit Workload and Visual Field Narrowing

  The mental processing capacity is limited or reduced due to talking, mental calculation, daydreaming, or the requirement to attend to two information sources simultaneously. When attention is focused on a central task, the ability to detect peripheral stimulus is reduced (Gasson & Peters, 1965; Lebowitz & Apelle, 1969). The National Aeronautics and Space Administration (NASA) conducted experiments where during a parallel task the pilot eye movement was observed to be reduced by 60% (Malmstrom, Reed, & Randle, 1982).

Williams (2008) provides a brief description of the human visual system limits. Williams (2008) suggests using four categories for the classification of visual information. The first category is foveal vision and is the most critical for object identification Williams (2008). Identifying and locating objects also depends on three other categories, including visual accommodation, peripheral vision ability, and color vision Williams (2008). These categories, as described by Williams (2008), are summarized below:

- Foveal Vision

Foveal vision helps bring into focus the information received by the human eye, which is in the form of symbols and images. Foveal vision is dependent on visual acuity which is the ability to resolve detail within the field of view. Foveal vision is associated with the fovea, which is a small depression in the retina of the eye. The fovea sends clear and sharply focused visual data to the brain. Foveal vision, which is the sharpest vision, represents a conical area of only about 1° of the visual field of view (Antunano, 2002).

A commonly accepted metric for the visual acuity of humans, expressed in terms of the angular size of an object, is a resolution of 1 minute of visual arc ($1/60^{th}$ of a degree) (O'Hare & Roscoe, 1990). This implies an object with a 1 ft visual cross-section can theoretically be resolved from a distance of 3,438 ft by the human eye since, at this distance, the object will subtend 1 minute of visual arc.

This theoretical limit for visual acuity can be degraded by environmental factors like low light levels and low contrast between an object and its background. Physiological factors including low blood oxygen levels, low blood sugar, alcohol, tobacco use, and sleep deprivation can also degrade visual acuity (Williams, 2008). Visual acuity is also degraded when an object falls outside of the 1° conical area of foveal vision (Williams, 2008).

The National Transportation and Safety Board (NTSB) states that in order for an aircraft to have a reasonable chance of being visually observed, it must subtend at least 12 minutes of visual arc (NTSB, 1987). This is equivalent to a distance of 286 ft for an object with a 1 ft visual cross-section (Williams, 2008). The Australian Bureau of Safety suggests that an aircraft should subtend a visual arc of 24 minutes to 36 minutes under sub-optimal visual conditions (Hobbs, 1991). This is equivalent to a distance of 95 ft for an object with a 1 ft visual cross-section (Williams, 2008).

- Visual Accommodation

Visual accommodation is the ability of the eye to adjust its focus towards a moving object as the distance between the eye and observer varies. Fatigue and age are two important parameters that affect visual accommodation. It can take the average pilot several seconds to accommodate a distant object (Hobbs, 1991). Visual accommodation can be affected by a lack of objects, for example starting into a clear sky hinders the eye's ability to focus over long distances. Similarly, if there are objects that are interposed between the object of interest and the viewer, visual accommodation can be affected (Williams, 2008).

- Peripheral Vision and Color Vision

The visual field of eyes typically covers about 190° to 200° on the horizontal plane and 120° to 135° on the vertical plane (Antunano, 2002) (Diffrient, Tilley, & Harman, 1981). Most of the visual information is processed within a very small portion of the central field of view. This central field of view is 1° in the vertical and horizontal plane. The peripheral vision is used to refer to the non-central field of view. The peripheral field of vision is responsible for conveying information related to the movement of objects both within the field of view and through space. The peripheral field of view comprises a portion that is sensitive to light (also called parafoveal vision) and a larger portion that is light insensitive. The parafoveal vision is estimated to be about 10° central field of view, but these estimates can vary (Gilbert, 1950). Information on color sensing can be processed within the widened field of view of parafoveal vision (Williams, 2008).

Williams and Gildea (2014) describe eight factors that influence the accomplishment of see-and-avoid task. These eight factors include small visual angle, cockpit obstructions, visual acuity, visual accommodation, poor contrast, complex background, lack of apparent motion, and visual search requirements.

- Small Visual Angle

  The visual angle does not increase linearly with the object's distance. This is due to the small visual angle present when the approaching object is theoretically visible. As the closing speed of the object increases, the time available to recognize the object when the object is large enough to be noticeable reduces (Williams & Gildea, 2014).

- Cockpit Obstructions

  Obstructions such as components of aircraft, passengers, aircraft propeller disk, windscreen glare and imperfections on the windscreen can inhibit the scanning task of pilots (Morris, 2005). Williams and Gildea (2014) state that "such objects can become focal traps, causing the eyes to focus at a closer distance than is needed to spot other traffic" (p. 6).

- Visual Acuity

  When outside of a 1-degree visual field center, visual acuity rapidly deteriorates. Williams and Gildea (2014) state that "factors that can affect the ability to focus, include age, fatigue, light/dark adaptation, and hypoxia." (p. 6).

- Visual Accommodation

  The act of focusing on an object is known as visual accommodation. The eyes are prone to focus at near distances when staring into empty spaces (Roscoe & Hull, 1982). This tendency is known as empty field myopia, and it can hinder the detection of objects at a further distance (Williams & Gildea, 2014).

- Poor Contrast

  The luminance difference between object and its background is known as contrast. The contrast increases as the luminance difference increase. Williams and Gildea (2014) state that "factors that can affect contrast are paint schemes, aircraft lighting systems, atmospheric conditions, and variations in background" (p. 6).

- Complex Background

  Complex background occurs when the luminance of the background varies, making the object difficult to discern from the background (Hobbs, 1991). Effect of complex background have a higher occurrence during air-to-air detections than during ground-to-air detections (Williams & Gildea, 2014).

- Lack of Apparent Motion

A moving object is considerably easier for the human visual system to identify and attend to than one that remains stationary within the field of view (Hobbs, 1991). Lack of apparent motion is a problem for manned aircraft pilots due to the traffic remaining in a stationary position during a collision course (Williams & Gildea, 2014).

- Visual Search Requirements

  Pilots can spend less than 30% of the time scanning for traffic due to workload and distractions (Williams & Gildea, 2014). Unlike a pilot, VO spends almost 100% of their time in traffic scans as a VO does not have other workload while scanning for traffic (Williams & Gildea, 2014).

Williams and Gildea (2014) identify vigilance as an important factor that affects the human visual system limit when a visual task is performed for a longer duration. Fatigue or boredom could deteriorate the ability of a VO to perform tasks such as scanning for intruder aircraft traffic. Studies have shown that vigilance decrements for such kind of tasks usually occur after 30 to 60 minutes have passed into performing the task (Boff & Lincoln, 1988). Other factors that affect vigilance include event rate, combinations of sensory modalities, multiple signal sources, source complexity, signal duration and intensity, observer skill level, intermittent versus continuous attention requirements, and task value (Parasuraman & Davies, 1977).

The FAA advisory circular (AC) 90-48D *Pilots' Role in Collision Avoidance* (FAA, 2016d) lists a few factors that affect the human visual system limits. The report categorizes these factors into six categories. According to (FAA, 2016d), these six categories include attention and response to traffic movement, refocusing eyes, refocusing when switching views, spotting threats, and nighttime searches.

- Attention and Response to Traffic Movement

  Based on previous research, a reaction time of 12.5 seconds is common for the average person. If detection means were to depend solely on see and avoid, this reaction time may be insufficient and can be dangerous as the target size decreases or the target speed increases (FAA, 2016d).

- Refocusing Eyes

  The detection probability of a potential collision increases as the time spent looking outside increases. The eyes revert to their relaxed state at a focal distance of 10 ft to 30 ft if there is no specific focus. Pilots should perform shift glances and refocusing during intervals for effective acquisition of a target (FAA, 2016d).

- Refocusing when Switching Views

  Due to piloting tasks, the eyes are required to switch from distant viewing and cockpit instrument viewing. This view switching causes the eyes to require several seconds to accommodate for focusing on either distant or near objects. The time required for the eyes to refocus is easily increased due to fatigue, boredom, illness, anxiety, or preoccupation (FAA, 2016d).

- Eye Movements

Short and regularly spaced eye movements are considered as the most effective strategy in terms of scanning. Pilots generally prefer horizontal back and forth eye movement. To enable detection, the eye movement should be limited to 10° and be performed for at least 1 second (FAA, 2016d).

- Spotting Threats

  Peripheral vision is highly beneficial towards threat collision spotting; typically, the first sign of a potential collision is apparent movement. Recognizing this visual cue aids in executing proper evasive maneuvers (FAA, 2016d).

- Nighttime Searches

  Nighttime visual search relies heavily on peripheral vision due to the night-blind spot that covers the area of 5° to 10° in the visual field center. Modern aircraft lighting systems greatly improve aircraft operational safety at night. However, the presence of ground lights that can conflict with the aircraft lights, make detecting aircraft more difficult. The utilization of night vision goggles brings up an issue where some LED obstructions or aircraft lighting may not be visible via the night vision goggles (FAA, 2016d).

Woo, Truong, and Choi (2020) noted in their paper the factors regarding human visual capabilities; these factors include visual acuity, retinal eccentricity, and contrast threshold.

- Visual Acuity

  An individual with 20/20 Snellen visual acuity can see and resolve image features as small as 1 minute of arc within their field of vision (Howett, 1983). A minimum visual angle of 0.2° or 12 arc-minutes was suggested based on an NTSB investigation (Gibb, Gray, & Scharff, 2010). The minimum visual angle suggestion is important as it allows the manned aircraft to be detected in order to have enough time to perform evasive maneuvers (Gibb et al., 2010). The size of objects vary in relation to their distance from an observer. Objects closer to an observer occupy more space in the observer's field of view, whereas more distant objects occupy a smaller space (Woo et al., 2020).

- Retinal Eccentricity

  Retinal eccentricity refers to the distance between the target image location on the retina and the center of the fovea. It is measured in degrees or visual arcminutes (Hirsch & Curcio, 1989; Westheimer, 2010). Retinal eccentricity is crucial during distant object search because the objects appear small when they are far away. When looking for far away objects, retinal eccentricity is significant because distant objects appear small, requiring the capacity to perceive fine detail (Wulfeck, Weisz, & Raben, 1958).

- Contrast Threshold

  Contrast threshold is a key attribute used in human visual search models that refers to the contrast between the target and its background (Woo et al., 2020). Multiple researchers have used various strategies to model the contrast effect. Poe devised his own methodology to establish a contrast threshold below which the likelihood of seeing an object falls below 50% (Poe, 1974). The object, a small target, as defined by Andrew as a target with a subtending arc size of 1 to 10 minutes (Andrews, 1984; J. W Andrews, 1991). Since detectability is proportional to the target area multiplied by the target's contrast, if the contrast is cut in half, the target size must be doubled to get the same level of detectability (Woo et al., 2020).

The FAA report on *Pilot's Handbook of Aeronautical Knowledge* FAA (2016b) addresses several complications with human vision during nighttime operational conditions. According to FAA (2016b), these additional complications include mesopic vision, scotopic vision, night blind spot, and dark adaptation.

- <u>Mesopic Vision</u>

  Mesopic vision results in a continuous decline in visual acuity in the cones corresponding to the drop in ambient light. This is observed during civil twilight and during lunar illumination (FAA, 2016b).

- <u>Scotopic Vision</u>

  This vision is defined by the lack of detail identification for small objects, color vision loss, and the formation of night blind spots during low-lighting periods (FAA, 2016b).

- <u>Night Blind Spot</u>

  Rods in the periphery become the dominant visual sensor during a low-light situation, creating a temporary blind spot in the central, foveal view of the eye (FAA, 2016b).

- <u>Dark Adaptation</u>

  Adjustment of the eye by increasing the rods' light sensitivity in order to adapt to a darker environment (FAA, 2016b).

2.1.2 Human Visual Performance Models

In this section, a few mathematical models of the human visual system developed to visually detect aircraft are reviewed.

Franklin and Whittenburg (1965) did extensive research on human visual performance models. The authors noted that a visual performance model should meet three criteria, and these criteria include:

- A model should be valid: the model should produce realistic predictions depending on the operational situation.
- A model should be straightforward and simple to use.
- A model should be adaptable to various situations in order to estimate performance from different nature of missions.

Franklin and Whittenburg (1965) also provide four different guidelines to satisfy the aforementioned criteria. These four guidelines include: models should be based on field data, models should have a minimum amount of variables, models should consist of operationally defined variables, and models should have the complete detection/identification response continuum (Franklin & Whittenburg, 1965).

- <u>Models should be based on Field Data</u>

Field data is crucial in the validity of the model. This is because field data is comprised of variables that have been determined based on actual field performance data, which will improve the probability of realistic model predictions. Utilizing a field database will also help satisfy the model simplicity criterion by allowing for direct correlations between target, environment, and aircraft variables regarding detection/identification performance. This reduces the need to introduce intervening assumptions about the visual observation process or capabilities (Franklin & Whittenburg, 1965).

- Models should contain Minimum Amount of Variables

  To satisfy model simplicity, the model should have the lowest number of variables required for "adequate" prediction. Whittenburg, Schreiber, and Richards (1959); Whittenburg, Schreiber, and Richards (1960); Whittenburg, Schreiber, Robinson, and Nordlie (1959) deduced that many of the single and combination variables can be neglected through a variable screening. This is because these variables have little to no probability of occurrence in the real world. A simple valid model should only contain necessary variables that illustrate the effect in the actual world and should neglect variables that do not considerably improve the model's predictive power (Franklin & Whittenburg, 1965).

- Models should consist of Operationally Defined Variables

  The variables of the model should be operationally defined for its ease of use. A definition is required that makes use of the resources and procedures that an operational user is likely to have on hand and that can be effectively utilized (Franklin & Whittenburg, 1965).

- Models should have the Complete Detection/Identification Response Continuum

  The adaptability of the model is satisfied through the inclusion of a variety of tactically appropriate responses. Whittenburg, Schreiber, and Richards (1959); Whittenburg et al. (1960) demonstrates that detection constitutes a continuum rather than a unique occurrence amongst the response of aerial observers. The continuum is distinguished by various levels of precision regarding the nature and identity of the target. A model must incorporate various response levels that are tactically appropriate to unique missions if the model is to be applied to missions of various types (Franklin & Whittenburg, 1965).

Franklin and Whittenburg (1965) note that for most models at that time, target detection performance is not only analytically driven and comprehensive, but also complicated (Gordon, 1963; Ornstein, Brainard, & Bishop, 1961; Ryll, 1962). The model developed by the authors is incomplete due to data limitations and because it is not comprehensive. However, the model is based on field data thus providing a reasonable approximation of the performance forecasts. The authors (Franklin & Whittenburg, 1965) utilized four steps for their approach in developing a preliminary model for predicting target detection. These four steps include selection of field data, preliminary model variables, composite variables, determination, and combination of best-weighted composite variables (Franklin & Whittenburg, 1965).

- Selection of Field Data

  A study conducted by Whittenburg, Robinson, and Hesson (1959) which collected field data under controlled conditions on a large number of targets that varied systematically in more than one dimension, provided a foundation for the preliminary model. Whittenburg, Robinson, et al. (1959) concluded in this study that most viewers either properly identified a target or completely missed it.

- <u>Preliminary Model Variables</u>

  The selection of variables had two constraints: information availability and operational concerns. Information availability is where a variable must be one whose effects are known, either from the literature in general or from the Whittenburg study's data (Whittenburg, Robinson, et al., 1959). The operational considerations constraint required that the values of variables in the model be specifiable by operational staff in order for the model to be effective for field prediction. These constraints resulted in the selection of eight out of 24 variables. These eight variables are size of target, shape of target, brightness contrast of target/ground, clutter, type of terrain, aircraft altitude, range, and speed. These eight variables are categorized into three composite variables that are size of target, distinctiveness of target, and time of exposure (Franklin & Whittenburg, 1965).

- <u>Composite Variables</u>

  Variables interact with each other to affect performance rather than independently during an operational situation. Three composite variables are formed through the combination of eight variables. The three composite variables include the apparent size of the target, the distinctiveness of the target, and the time of exposure (Franklin & Whittenburg, 1965).

  The apparent size of the target is dependent on the primary variables: target size, altitude, and range. The distinctiveness of a target is the combination of all primary variables related to how well the target contrasts with or stands out from its background. Time of exposure refers to the entire time a target is in the observer's field of view and could be recognized if the observer looked at it. The effective time of exposure depends on three general variables. These three variables include ground area size and shape determined by the observer, target position within the scanned area coupled with aircraft speed, and the reduction of overall exposure time by blocking the LOS between the observer and the target to account for terrain masking effects (Franklin & Whittenburg, 1965).

- <u>Determination and Combination of Best-weighted Composite Variables</u>

  The generation of best-weighted composite variables depends on the measurement of apparent size, distinctiveness, and exposure duration in the Whittenburg study (Whittenburg, Robinson, et al., 1959). A trial-and-error graphic solution was utilized to discover the combination of the three composite variables that would most precisely predict the actual detection/identification probability obtained for each target in the investigation. In the investigation, the multiplication of the square root of the target’s average apparent size, distinctiveness of target, and the effective time of exposure produced the composite variables with the highest correlation. The investigation included time as the deteriorating factor amongst the predictable composite variables (Franklin & Whittenburg, 1965).

Watson et al. (2009) conducted a study to examine whether a simple pattern visibility metric, Spatial Standard Observer (SSO), can accurately predict the visibility of simulated aircraft images. The authors conducted a literature review referencing an aircraft visibility prediction by Duntley et al. (1964); Harris (1973). This prediction represented the spatial summation properties of the human visual system by utilizing digitized photographs of three scale airplane models (DC-3, DC-8, Boeing 737) in three different poses (0°, 45°, and 90° from nose-on). Different ranges were simulated through the scaling of the aircraft image size. The atmosphere of different ranges was simulated by the attenuation of contrast. They found that one of the aircraft with a 45° angle from nose-on had a detection range of 18 km. However, the model in this study could only provide predictions for the limited scaled aircraft models and poses.

Watson et al. (2009) conducted their experiment by comparing SSO predicted values to the visibility of aircraft images using human observers. The authors developed an SSO, which is a new metric to calculate contrast threshold (metric for determining the minimum target contrast that can be reliably detected) for grayscale images by utilizing a data set (43 stimuli contrast threshold from 16 observers) from the ModelFest Research Project (Carney et al., 1999; Carney, Tyler, Watson, Makous, & Beutter, 2000; Watson, 2005; Watson & Ahumada, 2005; Watson & J, 1999).

Watson et al. (2009) note that the SSO might allow a ground observer, a pilot in another aircraft, or a UA pilot on the ground to monitor other craft remotely through a UA-mounted sensor to estimate the distance at which an aircraft of a given kind, size, and coloration could be seen. The authors used two types of stimuli that include Gabor patterns and rendered aircraft images. The Gabor stimuli is obtained through the multiplication of a Gaussian and sinusoid with a fixed Gaussian standard deviation of 0.5° and sinusoid frequencies of 0, 1.12, 2, 2.83, 4, 5.66, 8, 11.31, 16, 22.63, and 30 cycles/deg. The other stimuli are the images of aircraft, which were obtained through the 3D airplane model graphic rendering. The images of 10 different aircraft (AH-64D, B747, hot air balloon, C-17, Cessna 172, ERJ145, F-16, MQ-8 Fire Scout, Global Hawk, and MQ-9) were used for this study. The aircraft images were displayed on a gray background while utilizing a 56-year-old male (ABW), a 36-year-old male (CVR), and a 30-year-old female (ES). The authors presented the stimuli (constructed as digital movies) on a black and white CRT monitor (200 cd/m^2 luminance) where the observer binocularly viewed the display (natural pupils in a dark room).

Watson et al. (2009) found in their test at mid to high frequencies, ES and CVR, were more sensitive than either ABW or the SSO model, which suggested that for young, well-corrected observers, the SSO model might underestimate sensitivity and acuity. The results indicated that the SSO model was well matched to observer ABW's contrast sensitivity filter, but it underestimated observers ES and CVR's sensitivity. The SSO predictions examination agreed with the ABW observer but was above the ES and CVR observers that is consistent with Gabor targets. The results indicated that SSO reliably forecasted visibility differences across aircraft types that included wide shape ranges without degrees of freedom or modified parameters. The results also indicated that low spatial frequencies dominated large aircraft targets, and the SSO overestimated sensitivity at low frequencies. A head-on view had a higher fluctuation in threshold owing to the aircraft's position in relation to the observer compared to the side view and oblique view. The authors found that for a variety of aircraft photos, the SSO provided a good explanation of the contrast thresholds where the SSO accurately reflected the variations in threshold due to aircraft type, size, and direction, as well as interactions among these variables. The results also indicated that the default SSO function, and the contrast sensitivity functions for the three observers were derived from the new fits where the sensitivity and acuity of ES and CVR were greater than the SSO.

Watson et al. (2009) state in their discussion that the SSO provides a good contrast threshold prediction for various aircraft images. All the predictions are accurate after the model parameters are adjusted. This adjustment is necessary as the model slightly under-predicted the sensitivity for two of the observers. The authors further state that the SSO and the ModelFest population underestimates the sensitivity of young observers. This validates the threshold range estimates calculation by the SSO. The authors note that the SSO is a valuable tool as real-world empirical measurements of visual range for these factors (size, shape, orientation, brightness, and the brightness of the background sky) are clearly unrealistic.

Williams and Gildea (2014) briefly address the issue regarding the visual performance model. The authors identified that the complexity of a human visual ability model was one of the drawbacks of a visual performance model. This is because no visual performance model can encompass all the relevant factors of the human visual system's abilities. Relevant factors that cannot be easily implemented in a visual model include target and background contrast, navigation and artificial lights, size, orientation, visual clutter, and location of the target image on the retina (J. W Andrews, 1991; Watson et al., 2009; Williams, 2008).

Williams and Gildea (2014) also use an example of a visual model regarding the human visual performance model. The authors use the SSO model developed by Watson et al. (2009) which could calculate the minimum contrast and maximum distance threshold. During non-attenuating conditions, the model predicts that the detection range will reduce to below three miles when there is a 90% contrast reduction, this distance further decreases during different environmental conditions and aircraft color alteration. Williams and Gildea (2014) also reference Morris (2005) to state that in the analysis of a visual-scanning model, the probability of identifying a converging 40 ft wide target for a pilot scanning for traffic 33% of the time varied from 0.723 at 100 kts to 0.162 at 300 kts. Morris (2005) states that probabilities in the real-world are lower than the probabilities obtained from the visual-scanning model since the model does not take into account factors such as "obstruction of aircraft from view, poor conspicuity, imperfect scanning, and inadequate avoidance maneuvering following detection" (p. 362). Williams and Gildea (2014) conclude that since the majority of the visual models do not consider many variables that affect aircraft visual detection, visual models are not recommended for VO operations in estimating visual distance accurately. Williams and Gildea (2014) do, however, mention that visual models can be useful when planning certain operations.

Woo (2017) conducted an analytical study to understand parameters which most affected the ability of a manned aircraft pilot to visually locate and avoid a small UAS ranging in size from 0.2 sq. ft to 10.8 sq. ft. Woo (2017) used the known limitations of human vision and a Monte Carlo analysis to estimate the probability of detection with varying UAS size, manned and UA's speed, and visual contrast of the UA. Additional factors studied were the time required for the identification of the aircraft and reaction to the aircraft. The range of manned aircraft speeds was 60 kts to 160 kts. The results show no sUA was detected more than 40% of the time when the manned aircraft was traveling at 60 kts; a one-square-foot sUAS at most 3.0% of the time. As the manned aircraft speed increased, sUAS detection decreased; when the manned aircraft speed exceeded 140 kts, the sUAS was predicted to be detected by the pilot less than 1% of the time.

Woo (2017) concluded that the primary factors determining the visibility of an UAS were the speed of the manned aircraft and the size of the UA due to the required distance at which a pilot would need to detect the UAS to safely avoid it. Increasing the contrast of the UAS increased its apparent size, but not enough to significantly improve detection probabilities. Woo (2017) noted that lighting systems that would create enough contrast to appreciably improve detectability are not currently practical in terms of size. Woo (2017) states in (p. 124), "since advancement in electronic technology will produce ADS-B and other technologies with lower, more practical payload and power demands, the industry focus should be on the deployment of those types of solutions as possible."

Wallace, Kiernan, Robbins, and Haritos (2019) note that visual modeling is essential because it is used as a foundation in the determination of UA or other objects that can be identified visually by RPs or VOs (Woo, 2017). Wallace, Kiernan, et al. (2019) analyzed sUAS telemetry data recorded by a DJI AeroScope near an urban airport. They calculated the visibility of each sUA from the maximum flight distance that was computed from the telemetry data. They used the diagonal size of each sUA and obtained maximum visual arc detection distances based on Greening (1976)'s visual detection model. Wallace, Kiernan, et al. (2019) found that:

> "5.5% of UAS flights were "unlikely to be seen" with a visibility lower than one arcminute. 52.7% of UAS flights (58 flights) satisfied the minimal visibility standards, having a visibility of at least one arcminute. 12.7% of UAS flights (14 flights) were likely to be detected but not necessarily recognized with a minimum 10 arc-minute visibility. 11.8% of UAS flight (13 flights) were recognized 30% – 40% of the time with a minimum visibility of 15 arc-minutes. 14.5% of UAS flight (16 flights) were recognized more than 50% of the time with a minimum visibility of 30 or more arcminutes." (p. 12)

Wallace, Kiernan, et al. (2019) noted that the visibility of the UAS dropped to fewer than 10 arc-minutes when the UAS operated over 400 ft altitude. They also noted that apart from the largest sUAS, most sUAS were not likely to be seen for operations that exceeded distance of 4,000 ft.

Woo et al. (2020) provide a brief description regarding the human visual performance models. The authors reference the model that J. W. Andrews (1991) developed using two-dimensional solid angles as a foundation. J. W. Andrews (1991) developed the model through the extension of the Howett (1983) model which utilized a single dimension radian unit. J. W. Andrews (1991) utilized Koschmieder's law to model the reduction of the target contrast in an unclear atmosphere by multiplying the visual angle subtended by the target area and the target's contrast against its background to determine the aircraft sighting probability. The authors (Woo et al., 2020) utilized the Monte Carlo simulation to address the uncertainty of the human visual search performance model and the human performance model while eliminating covariance and dependency of input variables (Cohn, 1981; Papadopoulos & Yeung, 2001; Veneri et al., 2010).

Woo et al. (2020) developed the model by integrating Howett (1983)'s limits on human visual performance and the J. W Andrews (1991)'s algorithm for detecting targets while using the Monte Carlo simulation to adapt to very small targets. The authors utilized five main variables in this study. The model has two controlled input variables that are the manned aircraft speed and sUAS size. The remaining three input variables, including sUAS airspeed, heading, and contrast, are not directly controlled by the user. These variables get selected randomly in the Monte Carlo simulations within a pre-defined set of values. The authors conducted a simulation of aircraft with speeds from 60 kts to 160 kts by utilizing the new model. This speed range covers typical departure and arrival procedures for manned aircraft operations encompassing small light-sport aircraft to large transport aircraft.

Woo et al. (2020) demonstrated with their Monte Carlo method that pilots had at most a 39% probability of detecting an sUAS with sufficient time to avoid a collision. The greatest probabilities were for sUAS near the 55 lb weight limit and manned aircraft traveling at 60 kts. The likelihood of successful detection decreased to no more than a 3% chance for sUAS with a visible profile of less than 1.0 square foot; sUAS with a 0.2 square foot visible profile were essentially undetectable, even at a manned aircraft speed of 60 kts (0.1% probability). Woo et al. (2020) noted that at the minimum distance that allows pilots enough time to react and avoid a collision, the many of the sUAS had render image sizes near or below 1 arc minute, held as the lower limit for human visual acuity. Woo et al. (2020) additionally utilized artificially high values of contrast to assess its impact on detection. The increased contrast resulted in a 2% increase in detection probability. They note that while lighting can be used to increase the contrast, the required increase in light intensity would be several orders of magnitude greater than most current aircraft strobe lights.

The primary factors influencing the results presented by Woo et al. (2020) are the size of the sUAS (positively correlated with detection) and the speed of the manned aircraft (negatively correlated). Woo et al. (2020) note that despite the increase in likelihood of detection with increased sUAS size, even the largest sUAS are not reliably or even frequently detected. Increases in speed of the manned aircraft negatively impacted detection due to the increased range at which detection would allow for necessary time for avoidance. Woo et al. (2020) also note the effect of an increased manned aircraft velocity could be framed as a decrease in the allowable search time for the pilot to detect the sUAS.

Woo et al. (2020) conclude based on their new mathematical model results, that sUAS images do not usually become large enough to be viewed by manned aircraft pilots in time to avoid a collision. Woo et al. (2020) further state that the probability of a manned aircraft pilot detecting sUAS in time to avoid collisions is very low. Therefore, the see and avoid principle is not reliable in the case of sUAS detection.

2.1.3 VO Accuracy, Detection, and Reliability

This section provides a review of literature conducted by different researchers in terms of the accuracy, detection, and reliability of the VO. The accuracy, detection, and reliability of the VO are categorized into four categories in this section: manned aircraft visual detection by ground observers, manned aircraft visual detection by manned aircraft pilots, UAS detection by ground observers, UAS pilots, and control tower, and UAS detection by manned aircraft pilots and safety observers.

2.1.3.1 Manned Aircraft Visual Detection by Ground Observers

Wright (1966) provides a brief description regarding VO detection. The author studied the detection of a VO with the following goals:

- Establish the unaided capacity of observers to visually detect and recognize low-altitude airplane under ideal field conditions.

- Establish visual detection trends that are dependent on aircraft type, binocular use, and number of observers to determine the ability of the observers in aircraft range estimation.

Wright (1966) conducted a study utilizing 27 observers with a visual acuity of 20/25 or better. The response from the observers was recorded in terms of detection, estimated detection range, tentative recognition, tentative recognition range estimation, positive recognition, and positive recognition range estimation. The study found that for a jet aircraft, 50% of the time, the visual detection happened at a distance of 10,000 m which was found to be greater than results of previous studies (Frederickson, Follettie, & Baldwin, 1967; Wokoun, 1960; Zimmer & McGinnis, 1963). A recognition probability of 0.5 for a jet aircraft occurred with a tentative recognition happening at 6,500 m with 86.2% correct response, and positive recognition happening at 3,250 m with a 97.6% correct response. The study found that for a propeller aircraft, the detection probability of 0.5 happened at 8,800 m. Tentative recognition probability of 0.5 happened at 5,900 m with a correct response of 64.4% and the positive recognition probability of 0.5 happened at 3,300 m with a correct response of 89.5%. The study also found that binoculars increased the recognition range of the jet aircraft and propeller aircraft but decreased the recognition range when the jet aircraft was approaching head-on. The observer range estimation varied from mean overestimation and mean underestimation by 50%.

Frederickson et al. (1967) report the detection capabilities of the VO through four different tests, including aircraft detection, range estimation, structure identification, and auditory tracking.

- <u>Aircraft Detection Test</u>

  The test was conducted while using various types of visual aid to detect the aircraft by numerous independent observers under low sound pressure condition (less than 34 dB). These observers were rotated amongst 4 posts to make up for biases. The results were obtained based on 6 variable combinations. These variable combinations included eye vs ear, eye vs 6 x 30 binoculars, 6 x 30 vs 7 x 50 binoculars, 1 minute vs 5 minutes early warning, observer offset distance from flight path, and terrain masking degree (Frederickson et al., 1967).

  The results of the eye versus ear test found that the planes were detected visually 500 m before they were detected through auditory methods. However, under the near terrain masking conditions auditory detection and visual detection occurred at comparable distances, suggesting that the auditory sense could be used for initial detection under conditions of poor visibility. The result of the aided vs. unaided detection found that in far terrain masking, the aided vs. non-aided visual detection was not consistently different, with the average detection range being 12,000 m amongst the two of them. The results for the different visual aids found that the mean detection ranges for the two types of binoculars did not differ significantly.

  The results found that the difference in early warning time had no discernable changes in detection ranges. The results for the observer offset distance were statistically significant different where, as the observer offset distance from flight path increased, the average range of detection increased from 9,800 m to14,500 m (Frederickson et al., 1967).

- <u>Range Estimation Test</u>

The study conducted a range estimation test where the observers were asked to estimate distances ranging from 1,000 m and 5,000 m. The study found that as the distance of offset from flight path increased, the estimation algebraic error decreased, and the observers' response variability decreased. The study also found that "Observers underestimated the range by roughly 475 meters at the 200-meter observation post, whereas observers overestimated the range by roughly 50 meters at the 3,300-meter observation post." (p. vi) (Frederickson et al., 1967).

- Recognition of Aircraft Structure

  The study conducted this test by utilizing observers located at 200 m distance and 1,400 m distance for different classes of aircraft such as bombers and fighters. The result from this test found that unaided vision had a longer average response latency between the initial detection response and the first structure recognition response than binocular aided vision. The time it takes for the initial detection response to be followed by the first structure identification response was 2.7 seconds for a fighter jet with binoculars (Frederickson et al., 1967).

- Auditory Tracking

  The auditory test included eight observers who tracked nine flights of an A-6 aircraft, from the 2,000-meter observer post. The auditory tracking tests found that an untrained observer consistently tracked the target ahead of its position, with tracking errors occurring more consistently as the aircraft progressed from inbound to outbound and being the result of acoustic lag (Frederickson et al., 1967).

Baldwin, Frederickson, Kubala, McCluskey, and Wright (1975) conducted a series of tests to study the aircraft detection capabilities and aircraft range estimation capabilities by the VO on three different aircrafts (F-4C, A-6, and F-105D). In their review of earlier tests, Baldwin, Frederickson, Kubala, McCluskey, and Wright (1975) reference Wokoun (1960) on tests conducted at Gila Bend, Arizona where the mean detection range of an aircraft was 2,750 m with a 45° search sector, the mean detection distance was 2,585 m with a 90° search sector, and the mean detection distance was 1,985 m with a 360° search sector. Baldwin et al. (1975) also reference Zimmer and McGinnis (1963) on a test conducted at the White Sands Missile Range where the average range of detection with an early warning was 4,400 yards. Zimmer and McGinnis (1963) concluded that the range of detection is dependent on the heading angle of aircraft, altitude, and the speed of the aircraft.

Baldwin et al. (1975) reference a study conducted by the Human Resource Research Organization (HumRRO) (Wright, 1966) to state that the average detection range of an aircraft (with or without observer offset) across multiple viewing systems (aided vs. unaided search) were 10,000 m. This study also concluded that as the accuracy of early warning increased, the detection range also increased. Baldwin et al. (1975) reference the same study (Wright, 1966) for a minimum terrain clearance test where for the far terrain masking condition, the mean detection range averaged over all viewing situations exceeded 12,000 m.

Baldwin et al. (1975) conducted their own tests utilizing 16 observers who had range estimation training to perform a 180° sector area search with and without early warning. The results from this test found that for all test cases, the average detection distance of the aircraft was around 6,200 m. The authors also conducted range estimation tests where it was observed that the outbound aircraft were more accurately detected than inbound aircraft. The authors note that the magnitude of the errors produced by the observers during the test was greater than the magnitude of the errors made at the end of training. The authors also note from the post-trial questionnaire that 58 % of the detections occurred against a cloudy background, and 83% of aircraft were seen before they were heard. The authors note that 60% of the time, ground observers recognized the aircraft before the pilot detected the ground observers.

Williams and Gildea (2014) reference Watson et al. (2009) to mention that when compared to changes in aircraft orientation or contrast from the backdrop, changes in aircraft size or distance from the observer resulted in the highest changes in the observer's detection threshold. The author concluded that for airplane detection, distance is more significant than atmospheric conditions. The authors also reference Boff and Lincoln (1988) to mention that difficulties of keeping a watchful scan add to the difficulty of identifying approaching aircraft. The authors mention the work of Baldwin (1973) on manned aircraft detection by ground observers to summarize the following:

- Limiting the size of the search sector significantly impacts the distance at which airplanes are detected. The average detection range for search sectors of 180° and 360° was observed to be 1.25 miles, and for search sectors of 5°, it was observed to be 7.5 miles (Baldwin, 1973).
- Hand-held binoculars are ineffective and may result in poorer detection than unaided visual search with horizon blocking terrain features (Baldwin, 1973).
- The airplane approaching altitude impacts the distance at which airplanes are detected. Airplanes approaching the observers from an altitude of 500 ft Above Ground Level (AGL) were observed to be detected earlier than aircraft approaching from 1,500 ft (Baldwin, 1973).
- The observer offset distance from the flight path impacts the distance at which airplanes are detected. Airplanes were detected earlier when the observer moved away from the flight path (Baldwin, 1973).
- Specific search patterns techniques training may assist some observer's task performance while it is found to hamper other observer's task performance (Baldwin, 1973).

Williams and Gildea (2014) reference the document by the Society of Automotive Engineers (2003) that provides important recommendations on the minimum criteria for VO to fulfill their role. The recommendations are derived from a study of safety observers that utilize laser beams to observe the airspace. The minimum criteria include the physical capacities of the observers, such as visual and auditory abilities, as well as restrictions on the use of drugs and alcohol. Williams and Gildea (2014) provide another set of recommendations from the Society of Automotive Engineers (2003) to mention that 1) it takes at least 30 minutes for an observer to become fully acclimated to the dark, and 2) exposure to bright lights or the use of tobacco products can cause a delay to become fully acclimated to the dark.

2.1.3.2 Manned Aircraft Visual Detection by Manned Aircraft Pilots and Safety Observers

The NTSB (1987) describes a study based on alerted and unalerted search tests of other aircraft by pilots. The results from the unalerted search test found that visual acquisition was achieved for 36 out of 64 encounters with an average detection range of 0.99 nm and a maximum range of 2.9 nm.

The result from the alerted search test found that visual acquisition was achieved 57 out of the 66 encounters with an average range of 1.4 nm. Another finding from this report is that since the Traffic Alert and Collision Avoidance System (TCAS) can identify the relative bearing, range, and altitude of the target aircraft, the acquisition probability of the pilots increased to 95% from 30% with a TCAS system on board.

Graham (1989) briefly describes a few points regarding factors affecting accuracy, detection, and reliability of manned pilot detection of manned aircraft. The author references Applied Psychology Corporation (1962); FAA (1961) on the effect of fluorescent and nonfluorescent paints, as well as paint/pattern contributions to aircraft detection ranges and observer flight attitude estimation. The result from the "Field Study of Threshold Ranges for Aircraft Detection and Color Identification" study found that first detection occurred 80% of the time in a negative contrast; a 9% detection rate was observed in both positive and negative contrasts; an 8% detection rate was observed in a positive contrast; and a specular reflection resulted in a 3% detection rate (FAA, 1961). The result from the "Outdoor Test Range Evaluation of Aircraft Paint Patterns" study found that although some paint patterns were slightly better than no pattern, attitude judgment of the observer in terms of roll, pitch, and heading was not significantly altered with paint pattern (Applied Psychology Corporation, 1962). Graham (1989) concluded that the threshold detection ranges for aircraft with fluorescent and nonfluorescent paint showed no significant differences when the contrast was similar (Federman & Siegel, 1973). However, fluorescent colors were observed to be detected at further ranges than nonfluorescent colors when there was a reduction in contrast.

Hobbs (1991) describes six different categories that affect the capabilities of a manned aircraft pilot for the see and avoid principle. These categories include background contrast, effect of atmosphere, paint schemes on the aircraft, lack of relative motion on a collision course, small visual angle presented on an approaching aircraft, and complex background effect Hobbs (1991).

- <u>Background Contrast</u>

  The contrast between a target's brightness and its background's brightness is a crucial detectability determinant (Andrews, 1977; Duntley, 1964). The contrast between the airplane and its surroundings is more important than the aircraft color. However, in certain cases, the airplane's color scheme will maximize the contrast between the aircraft and its background, depending on the background's luminance (Hobbs, 1991).

- <u>Effect of Atmosphere</u>

  Haze or fog can scatter light, causing a reduction in contrast. This reduction in contrast is due to some light from the airplane being dispersed away from the observer while background light being scattered onto the eyes of the observer (Hobbs, 1991). Good visibility conditions do not always result in an ideal contrast level (Harris, 1979).

- <u>Paint Schemes on the Aircraft</u>

  Graham (1989) concluded that aircraft painted in fluorescent colors are not easier to spot than aircraft painted in nonfluorescent colors. Trials indicated that the airplane was darker than its surroundings in 80% of preliminary detections (Graham, 1989). Hobbs (1991) summarized that poor background contrast against the aircraft is caused by the following four factors: (1) light aircraft against light background, (2) dark aircraft against a dark background, (3) low background luminance, and (4) the presence of atmospheric haze.

- Lack of Relative Motion on a Collision Course

  The human visual system is limited in its capabilities at detecting motionless objects compared to detecting movement. In the pilot's visual field, an aircraft on a collision course will normally appear to be a stationary object due to the geometry of collision flight paths. If the impact flight paths are straight at constant speeds, then the relative bearing will remain constant up until the collision point (Hobbs, 1991).

- Small Visual Angle Presented on an Approaching Aircraft

  Until a short time before contact, an approaching high-speed aircraft will present a narrow visual angle (Hobbs, 1991). A pilot's ability to identify an incoming aircraft in time to take evasive action may be hampered by the aircraft's narrow visual angle due to the visual acuity limitations (Steenblik, 1988). For slower aircraft and head-on encounters, the small visual angle may not be a severe issue (Flight Safety Digest, 1989; Hobbs, 1991).

- Complex background effect

  Pilots looking for traffic have a considerably more difficult task because aircraft frequently appear against complex backgrounds of clouds or topography. The ‘contour interaction’ in which the outline of a target interacts with the contours present in the background or in nearby objects is a prominent source of interference (Wolford & Chambers, 1984). At lower altitudes, where aircraft appear against complicated backgrounds, contour contact is most likely to be a concern. (Wolford & Chambers, 1984).

Colvin, Dodhia, and Dismukes (2005) reference Baker (1960); Smith and Lucacini (1969) to state that during target searching or the monitoring of rare events, humans have poor capabilities on the maintenance of vigilance. The authors referenced a flight test study conducted by Howell (1957) where pilots encountered conflicts with other aircraft. In this study, nine out of the 128 conflicts were not detected. In the case of successful detections, the mean detection ranges were between 3.4 miles and 5.4 miles with or without the influence of early traffic encounter warnings (Howell, 1957). The study found that participants spent just under a third of their time looking outside the cockpit except during the traffic phase when gazing outside jumped to 51%. The study also found that the scanning of the center-front windscreen by pilots was adequate most of the time, but not always, and scanning of the left and right sides of this windscreen was adequate less than half of the time. Colvin et al. (2005) reference the study on an examination of collision geometries for rates of ascent and descent typical of civil aircraft (Fries, 2004) to claim that pilots only need to scan around 3° above and below the horizon to prevent collisions.

Watson et al. (2009) reference the work of Andrews (1977) to state that a thorough examination of the see and avoid problem depends on the following: visual search, view field, target approach angle, target approach speed, and target detectability. Watson et al. (2009) reference Howell (1957) to state that the detection range was observed to be between 5.5 km and 8.7 km for detection of a DC-3 on a collision course approach. When the target aircraft approach angle was known, the detection range was improved to be between 17.3 km and 23 km. Watson et al. (2009) reference Graham (1970) to conclude that the failure of target detection leads to the failure to see and avoid.

Kephart and Braasch (2010) conducted a study to compare detection ranges of an intruding aircraft by manned aircraft pilots and a camera system during daylight Visual Meteorological Conditions (VMC). The authors performed two separate tests. The first test was to evaluate the in-flight visual detection performance of manned aircraft pilots. Each of the seven pilot participants were required to detect a Piper Warrior III while flying a Piper Saratoga. The pilots were to detect the Piper Warrior III in a head-on and 90° intercept encounter. The second test was to evaluate the detection performance of a camera system. The second test mainly focuses on camera detection performance. Three cameras with a field of view of 40° horizontal and 30° vertical were installed on the Piper Saratoga to provide a total horizontal field of view of 120°. The cameras were installed behind the windshield of the Saratoga. The cameras were to detect a Cessna 210 Centurion while in a head-on and 90° intercept encounter with the Saratoga. All three aircrafts were outfitted with Global Positioning Systems (GPS). Once detection was confirmed the position information from the GPS and the recorded detection time was used to calculate the detection range. Results from the study found that the average detection range of the intruder aircraft by manned aircraft pilots was 1.275 sm, with average head-on encounters detection range of 1.038 sm and average 90° intercept encounters detection range of 1.511 sm. Average detection range by the camera system was 0.521 sm, with average head-on detection range of 0.417 sm and 90° intercept detection range of 0.651 sm. Based on the test, Kephart and Braasch (2010) concluded that manned aircraft pilots detected the intruder aircraft faster than camera system.

Williams and Gildea (2014) reference Howell (1957) to mention an aircraft detection test which found that when informed of the approach direction, an observer could detect a DC-3 at a range of 17.3 km to 23 km. This detection range was reduced to 5.5 km to 8.7 km when the observers were entrusted with an uninformed search duty. The authors note that a VO has a greater detection probability compared to a pilot that typically only spends 35% of their time on traffic detection. The authors also note that a VO is less likely to have obstacles obstructing their view but may be affected by empty field myopia when looking up to the sky.

Williams and Gildea (2014) mention the study of Croft, Pittman, and Scialfa (2007) that (Croft et al., 2007) obtained a 30% search success rate by a Search And Rescue (SAR) spotter. The authors note that this is an improvement over the 12% search success rate obtained by Stager and Angus (1975). Croft et al. (2007) attribute this improvement in the success rate of the SAR spotters to a significant number of gaze fixations that were spaced somewhat close together. The high number of gaze fixations caused hit rates to increase when both central and peripheral visual function was functioning optimally. Croft et al. (2007) suggest while training affected the success rate, other factors like SAR spotters having to examine only between 17% and 31% of a specific region before they changed spots, also played a role in the higher success rate. Compared to SAR spotters, VOs don’t change their spots. However, VOs could fail to detect a moving aircraft if the observation region is large.

2.1.3.3 VO/RP Performance in UAS Operations

Williams and Gildea (2014) conducted a literature review on UAS VO performance. The authors describe experiments conducted by Crognale (2009) to evaluate UAS VO effectiveness. The authors also describe the work of Dolgov, Marshall, Davis, Wierzbanowski, and Hudson (2012) that evaluated the UAS VO performance for operations during the day, dusk, and night.

The first article that Williams and Gildea (2014) mention, was the Crognale (2009) article which utilized 15 different observers to detect a Scan Eagle UAS with a 40 lb. weight and 10 ft wingspan. The experiment was designed so that the UAS approaches the observers head-on. The UAS was placed 1.5 km (0.93 miles) from the observers and approached the observers from an unknown direction. Two different UAS – one painted gray and one painted orange were used in the experiment. Observers wore earplugs to prevent the sound from the UA from aiding in the identification of the position of the UA. The observers achieved a detection rate of 97% amongst 240 flight trials with an average detection range of 327 m (1,073 ft). A detection range of 327 m would allow a pilot 13 seconds to undertake a collision avoidance maneuver for these UAS at typical cruise speeds. The rate of successful detections decreases from 97% to 49% if a successful detection is defined as a detection that allows 12 seconds of response time based as suggested by Edmunson (2012). Crognale (2009) also points out that the VO's actual performance was significantly lower than that predicted by the SSO model, which predicts a detection range of 800 m to 1,500 m. This difference between the VO's performance and the SSO prediction is due to the observers' scanning inefficiencies, as well as the high degree of uncertainty associated with the target's location.

The second experiment Crognale (2009) conducted utilized 14 observers to estimate the distance and altitude of a Scan Eagle UAS at 10 selected orbit points. Combinations of three different distances (0.25, 0.5, 0.75 miles) and three different altitudes (500, 1,000, 1,500 ft) were used to define the orbit points. Results from this experiment indicated that the observer's performance in estimating the distance and altitude of the UAS was not satisfactory. The average estimation error for distance was about 40% more than the actual distance. The average estimation error for altitude was about 60% from the actual altitude.

In the third experiment, Crognale (2009) utilized observers to estimate detection distances when the UAS position was fairly well known. The observers tracked the flight of the UAS and noted the distance at which they could not detect the UAS as it flew away from them. Then, as the UAS flew back towards the observers, they noted the distance at which they could again detect the UAS. The results from this experiment indicated that the mean detection range of the UAS as it flew away from the participants was 1,276 m (4,186 ft), and the average detection distance to reacquire the UAS was 898 m (2,946 ft). Both of these values are greater than the value of 327 m obtained from the first experiment but are similar to the values obtained from the SSO model. Based on these results, Williams and Gildea (2014) assumed the improvement in the detection distance was due to the reduction in the search area.

Crognale (2009)'s fourth experiment, studied the ability of VOs to assess the potential for a collision between the Scan Eagle UAS and an intruding aircraft. It was found that the VOs could not assess the likelihood of a collision unless they could see both the airplane and the UAS at the same time. Crognale (2009); Vance et al. (2017) concluded that if the UAS inbound position was unknown, VO performed poorly at visually acquiring UAS platforms. Crognale (2009) suggested that it was also possible that relative motion would aid in the detection of aircraft targets. One of Crognale (2009)'s most significant finding was that in unclear scenarios (without audible signals, TCAS, or radio announcements), visual detection by VO was unlikely to contribute considerably to collision avoidance.

Dolgov et al. (2012) conducted experiments to evaluate the UAS VO performance for operations during the day, dusk, and night. The experiments also determined the ability of the observers to determine if an intruder aircraft in the airspace was on a collision path with the UAS. The key conclusions of their study were:

- There was not much difference in the performance of the observers between day and night operations, and the night operations were deemed to be favorable based on the visibility metrics used in the study.
- During the night, manned aircraft were detected further away compared to the daytime. This was not true for the UAS utilized in the study.
- The performance of the observers in predicting the likelihood of a collision varied substantially, but was generally poor.

Stark, Smith, Navarrete, and Chen (2015) in their study, developed supplemental UAS operations protocols to minimize risk during nighttime conditions. The authors' proposal was based on tests conducted using a fixed-wing foam UAS fitted with a new lighting system. The first recommendation by Stark et al. (2015) is to ensure RPs and VOs complete a site inspection during the daytime to identify potential visual obstructions that could lead to collisions during nighttime operations. The second recommendation by Stark et al. (2015) is to ensure RPs and VOs complete training on determination of UAS orientation using only external lights on the UAS. According to Stark et al. (2015), for a fixed-wing UAS with a wingspan of 8 ft, complete determination of UAS orientation is possible only up to distances lesser than 1000 ft, however determination of UAS heading and roll may be possible up to distances lesser than 2 nm. The third recommendation by Stark et al. (2015) is to utilize a secondary VO, who is located at a distance from the RP and can relay information on visual obstacles and intruding air traffic to the RP.

Stark et al. (2015) draw the following conclusions for the RP experience from their study (p. 258):

- "Too much ambient light results in disorientation."
- "Too much light on the aircraft is too distracting."
- "The pilot needs a VO that can assist in radio communications between the pilot and the GCS, transportation of the pilot if need be and illumination of landing strip."
- "Red light must be used by anyone in close proximity to the Pilot in Command (PIC) prior to and during operation."

Stark et al. (2015) draw the following conclusions for the VO experience from their study (p. 258):

- "Similar to PIC, too much light on the aircraft is too distracting."
- "Ensure all necessary pre-flight preparations."
- "Ensure crew readiness prior to launch."
- "Difficult to confirm cord was detached from hook when using the catapult launcher."
- "VO needs to follow proper radio communication protocol, including repeating every message for clarification."
- "Constant scan for air traffic is needed to help PIC."

Dolgov (2016) conducted an experiment to determine VO capabilities for maintaining line of sight with a manned aircraft and an UA. During the experiment, the VOs were required to anticipate potential midair collision even during the loss of visual contact. The experiments were conducted in a desert that was free of light pollution by artificial sources. Dolgov (2016) conducted 24 trials during day, night, and dusk conditions. The author utilized three male visual observers, aged 22 – 32, who completed a course on VO training and were equipped with real-world VO duties experience. The VOs were informed before the trials about the location of the operating area where the sUAS was stationed via radio calls. The study utilized a variety of aircraft which includes a Flight Design CTLS manned aircraft (wingspan of 8.5 m, length of 6.2 m, and height of 2.2 m), a Raven RQ-11 B sUAS (wingspan of 1.4 m, weight of 1.9 kg, standard lighting system), and a Wasp III sUAS (wingspan of 72 cm, weight of 430 g, standard lighting system).

The result from the experiment by Dolgov (2016) indicated that the averages for the percentage of trials that VLOS was maintained by the VO for the CTLS during the day, dusk and night were 82%, 89.8%, and 87.4% respectively; the averages for the percentage of trials in which VOs kept VLOS for the Raven during the day, dusk and night were 36.1%, 83.9% and 73.6% respectively; the averages for the percentage of trials in which VOs kept VLOS for the Wasp during the day, dusk and night were 19.5%, 52.1%, and 75.0% respectively. The results from the percentage of trial time that VLOS was maintained by the VOs for the Raven and Wasp indicated that the time of day had a statistically significant effect. For the two UAS, the VOs maintained VLOS better at night and at dusk than during the day.

The results from the experiment found that the time of day had a considerable and statistically significant impact on the mean visual acquisition distance (VAD) for the CTLS and for one of the sUAS. The mean VAD for the CTLS was 1.28 km (day), 2.02 km (dusk), and 2.09 km (night); the mean VAD for the Raven was 0.72 km (day), 1.00 km (dusk), and 0.83 km (night); the mean VAD for the Wasp was 0.76 km (day), 0.56 km (dusk), and 0.76 km (night). Following univariate analyses, the effect of time of day was found to be statistically significant for Raven VADs but not for Wasp. The VAD for Raven was further at dusk than at daytime.

The amount of time it took the sUAS pilot to conduct an avoidance maneuver was calculated using the observers' average VAD and the average speed of the CTLS aircraft (around 78 kts). This time was calculated to be about 32 seconds (day), 51 seconds (dusk), and 52 seconds (night). Based on the TCAS defined traffic alert and resolution advisory zones by FAA (2011b), the CTLS detection during dusk or night was detected within the traffic alert zone with a greater margin to plan and perform evasive maneuvers. In contrast, the CTLS detection during the day was detected within the resolution advisory zone (35 seconds or less to a near midair collision).

The analyses of variance conducted by Dolgov (2016) revealed that while the time of day had no effect on observers' ability to maintain VLOS to the CTLS, it did have a substantial impact on the observers' ability to track the Raven and Wasp. Both sUAS had poor tracking performance during the day, however there was no statistical difference between dusk and night tracking. The authors attribute this to the additional sUAS lighting equipment utilized during dusk and night.

In the experiments, the participants were tasked to be the critical VO who was the only team member to communicate with the RP. In addition to the critical VO, the research team consisted of two safety VOs, one located on the ground and another in the aircraft. For half the trials, the critical VO and the RP were located beside each other to facilitate verbal and non-verbal communication. For the other half of the trails, the critical VO and the RP were separated from each other and communicated with each other via a radio. Field notes from the study indicated that when the critical VO and sUAS pilots were co-located, they were able to engage in non-verbal communication and interactions that were not broadcasted over the radio. This resulted in an increase in their situational awareness and improved operational flow. The critical VO had the advantage of position telemetry with little communication barrier when standing next to the sUAS pilot.

The field notes in addition to the interviews noted that VOs' usage of visual assistive technology varied at night but was rather consistent during the day. Even though night vision goggles were utilized for spotting and maintaining visual contact of an aircraft, binoculars were utilized more for resolving the identity of any ambiguous aircraft. However, both the binoculars and night vision goggles were impractical for anticipating a midair collision due to the magnification (binoculars only) and limited viewing angles (both binoculars and night vision goggles). This impracticality reduced the situational awareness of the observer. The VO stated that the assignment was particularly difficult since they were told to disregard the vertical separation.

The sUAS pilots commented that VOs successfully accomplished collision anticipation tasks when trajectory estimation strategies as described in Duke and Rushton (2012)’s study were utilized. The trajectory estimation strategies were similar to the tracking of an object projected on a flat plane rather than maintaining a linear optical trajectory (Shaffer, Marken, Dolgov, & Maynor, 2013). VOs could notify the sUAS pilot of the relative approach direction whenever two aircraft appeared to approach one another, this is due to the angular relationship between trajectories in the visual projection plane. The sUAS pilot could then determine a safe course of action and respond accordingly by utilizing simple strategies based on visual plane geometry.

Dolgov (2016) mentions that the limitation in his study was due to the small number of participants and the austere conditions in which the study took place. Because of these limitations, it would be impossible to extrapolate the results to all possible sUAS operational scenarios. Additionally, the author mentions that the conclusions are limited to UAS platforms of similar size since only a small UAS were utilized in this study.

Vance et al. (2017) conducted an experiment to study the effectiveness of VO at detecting a closing general aviation aircraft and estimating the accuracy of altitude, range, and closure rate of sUAS to inbound aircraft. The study utilized a Cessna 172/S (36 ft wingspan) and a DJI Matrice 100 (27 in width). Participants acted as VOs for a UA operation at a remote controlled (RC) airfield at dusk. Each participant was tasked with helping a RP to detect and avoid the Cessna 172/S conflict aircraft. The participants were separated from control equipment and information displays and interacted only with the assigned researcher, not the actual RP. Even though the altitude of the sUAS and aircraft were locked at 400 ft AGL and 600 ft AGL respectively, participants were still required to estimate altitude during each intercept. The authors assessed the results in terms of detection, estimation, and qualitative criteria.

- <u>Detection</u>

  Vance et al. (2017) report the VOs successfully detected the manned aircraft both by aural and visual means for all 49 intercepts with the average auditory detection distance of the aircraft was 8,605 ft and the average visual detection distance was 8,618 ft. For all practical purposes, these average detection distances are equivalent. The authors note that while the average detection distance from this study was significantly larger than the 1073 ft found by Crognale (2009), the difference is logical due to the difference in visible cross-section between the Cessna 172/S used in this study and the Scan Eagle UAS used by Crognale (2009).

When comparing individual intercepts, the VOs detected the aircraft through aural means by an average distance 159 ft further than visual means. The similarities in the detection ranges is consistent with the reporting from the participants that 30.5% of intercepts were first detected through auditory means, 27.1% visually, and 32% were detected by both means roughly simultaneously. The authors note that there were some uncommon cases where detection distance differed between the two senses by more than 2,640 ft (0.5 sm). They further note that this difference could lead to a situation where a VO can hear an aircraft but is unable to visually acquire it.

- Estimation

  VOs estimated the time before the intercept of the sUAS and aircraft. The 40 potential intercepts had an average time-to-intercept of 54 seconds. Vance et al. (2017) report that on average the participants overestimated the time to intercept by 17 seconds with 26 of the intercept times being overestimated and 11 underestimated.

  The VOs were asked to estimate the distance between the Cessna 172/S and the sUA at the point they believed the airframes closest to each other. Similar to the time estimates, the average distance was overestimated by 290 ft. The authors noted that the results for distance estimation were consistent with the results from Crognale (2009)'s study in terms of estimation variability and poor accuracy.

- Qualitative Findings

  Four of the ten VOs reported difficulty in assessing distances due to the difference in sizes of the sUA and manned aircraft. Vance et al. (2017) note that this is not a surprising result due to the lack of reference objects in the participants' field of view. Several participants also noted difficulty in assessing the difference in altitude between the two aircraft. Multiple participants additionally commented on the relative difficulty of discerning differences in altitude and potential of collision opposed to lateral distances. Eight of the participants and even one of the research team noted a strong optical illusion on 19 of the 39 intercepts, leading them to perceive collisions to be more likely than was true (Vance et al., 2017). This illusion was created when the aircraft and the sUA were in proximity to each other and were relatively close or overhead to the VOs. Several participants ended up perceiving the sUA and the aircraft to be at the same altitude, despite having been informed of the fixed altitudes of the aircraft before starting.

Vance et al. (2017) conclude that the detection distances, while consistent, should be treated as maximum detection distances, as conditions for the study were idealized. The authors provide a list of factors including aircraft size, sun position, and visual obstructions that could hinder visual detection. With respect to distance estimation, the authors note that VOs were 2.5 times more likely to overestimate distances rather than underestimating them, consistent with Crognale (2009)'s conclusion that VOs are poor at estimating distance and altitude accurately.

Based on the error in intercept times with respect to the average intercept time, Vance et al. (2017) conclude that there is a significant risk of RPs not having enough time to avoid a collision. The authors note that according to FAA (2016d), detecting and recognizing an invading flying object, assessing its collision potential, making an avoidance decision, and initiating and completing an avoidance maneuver takes a pilot 12.5 seconds. Vance et al. (2017) state that RPs would follow similar procedures which they estimated could take longer than the 12.5 second estimate.

Vance et al. (2017) recommend that information provided solely on the bases of VO reports be given a large safety buffer due to the frequency of perceptual illusions, which negatively impacted VO performance. They stress that both RPs and VOs need to remember that relative distance and collision potential assessments are less accurate as aircraft approach each other, especially when the aircraft are overhead or when lateral offsets from the observer are small.

Lennertz et al. (2018) conducted a study to examine commercial and hobbyist sUAS pilots' (18 participants) ability to estimate their ownship's altitude during a realistic flying task. Lennertz et al. (2018) referenced research by Williams and Gildea (2014); Woo (2017) which indicated that the human visual system alone might be insufficient to meet some of the requirements of Part 107 operations (FAA, 2016e). In particular, estimating the altitude of the sUAS by a RP or a VO may be difficult especially if they are engaged in other concurrent tasks (Lennertz et al., 2018).

In the study conducted by Lennertz et al. (2018), participants were required to fly a DJI Phantom 4 Pro to three different set altitudes (50 ft, 200 ft, and 350 ft). In each trial, participants flew the sUAS, then hovered at what they thought was the appropriate altitude and photographed a target. The researchers collected altitude readings and distributed questionnaires and instructions to the sUAS pilots. The research was carried out in a Class G airspace, during the daytime, under VMC. The flying site was a level field with few visual clues for altitude estimation. However, although the participants were not given height or distance information, there were trees, telephone poles, and a highway that could be seen from several hundred yards away. The results from this study were categorized into six categories. These categories include altitude measures, estimation accuracy, absolute altitude vs. barometric altitude, confidence rating, strategies and factors influencing altitude estimation, and task difficulty and workload (Lennertz et al., 2018).

- <u>Altitude Measures</u>

  Two types of altitudes (barometric altitude and absolute altitude) were utilized in this study. Barometric altitude is the AGL height of the sUAS measured through differences in barometric pressure at take-off and at the current altitude. The absolute altitude is the actual distance between the ground and the sUAS. The accuracy of altitude estimation relies on utilizing the absolute altitude as the dependent variable due to the height-off-the-ground as a basis for estimates by the pilots (Lennertz et al., 2018).

- <u>Estimation Accuracy</u>

  The distribution of participants' achieved altitudes was used to determine overall accuracy. The majority of participants' estimates were below the permitted altitude, with 52% of altitude estimates falling below the prescribed altitude of 50 ft and 89% of altitude estimates falling below the prescribed altitude of 200 ft and 350 ft (Lennertz et al., 2018).

  The comparison test between the average achieved altitude and participant's altitude estimates demonstrated that the participants' estimates of 50 ft were close to the actual 50 ft. Participants' achieved elevations were much lower when estimating 200 ft, with an average of 148.4 ft. They were also much lower when estimating 350 ft, with an average altitude of 247.4 ft. This indicates that participants' estimation error varied greatly based on the required altitude. Based on the pairwise comparisons using Fisher's Least Significant Difference test, the authors mention that the average deviation from prescribed altitude increased as recommended altitude increased. The results also showed that pilot's experience had no significant effect on this deviation. The inaccuracy in estimation did not improve even with practice (Lennertz et al., 2018).

- Absolute Altitude vs. Barometric Altitude

  The results indicate that at the higher altitudes employed in this study, pilots are poor at estimating sUAS absolute altitude. Barometric altitude is sometimes displayed for certain sUAS operations. It is calculated using a standard day temperature of 15°C, and any deviation from that temperature will result in errors on the sUAS display. In this study, barometric heights were 7.5 ft higher on average than participants' absolute altitudes, a statistically significant difference (Lennertz et al., 2018).

- Confidence Ratings

  Participants' confidence did not differ significantly based on their pilot experience, and confidence did not improve with successive trials (Lennertz et al., 2018).

- Strategies and Factors Influencing Altitude Estimation

  Participants were required to report any tactics they used to estimate the altitude of the sUAS, as well as what circumstances influenced that estimation. According to Lennertz et al. (2018), the strategies that the participants used to estimate altitude were as follows (p. 11):

  - The height of visual cues in the surrounding areas or imagined visual cues were used to estimate the altitude of the UAS.
  - Referenced the size of sUAS in the sky or on the screen.
  - The ascent rate was utilized in aiding with the altitude estimation.
  - Guessed the height of the UAS without using any references.
  - First made a note of the viewing angle for a given height estimate. From this, the participants increased the angle and subsequent height in increments to get the prescribed altitude estimate.

  Participants were also required to identify factors that influenced altitude estimations. According to Lennertz et al. (2018), factors that influenced altitude estimation were as follows (p. 11):

  - Distance between the pilot and the sUAS/cones (orange traffic cones were used as landmarks to establish and calculate altitudes in the experiment).
  - Scarce visual references influenced the estimation of altitude.
  - Altitude estimation was influenced by caution/desire not to exceed prescribed altitude.
  - Other factors: Limited experience; The DJI Phantom 4 Pro's small size made it appear further away than it actually was.

- Task Difficulty and Workload

  The results found that all 18 participants assessed the task's complexity as "easy". While three participants mentioned that there were no factors that affected their workload, the majority of the participants listed various factors. The common factors mentioned are wind, cold temperatures, the presence of the experimenters, and the ease and functionality of the DJI Phantom 4 Pro (e.g., auto-hover) (Lennertz et al., 2018).

Lennertz et al. (2018) mention that despite the differences in their background, hobbyist and commercial pilots performed similarly, indicating that experience had little bearing on performance. Lennertz et al. (2018) note that both groups of pilots had identical results in guessing the three different altitudes. They also found that the participants' ability to estimate altitude did not benefit from practice without feedback. They specify that one of the main findings indicated that participants are often bad at estimating the altitude of an sUAS, often overestimating the altitude of the sUAS especially when it is located at higher altitudes. This resulted in the majority of participants flying lower than instructed, especially at greater altitudes. Lennertz et al. (2018) note that the presence of a reliable visual reference, and/or accurate feedback may result in the improvement of estimating higher altitudes.

The altitude overestimation results suggested that in real-world operations, sUAS pilots are cautious and would likely fly their ownship below 400 ft. However, Lennertz et al. (2018) noted that the behaviors of participants may have been affected due to the presence of the experimenters. During the experiment, a minority of cases exceeded the prescribed altitudes greatly (over 400 ft). Considering this, Lennertz et al. (2018) specify that it is critical to have error mitigation methods during actual operations.

In addition to VO altitude estimation, the study also sought to demonstrate the variability in measured sUAS altitudes. The study found significant differences in the absolute altitude and barometric altitude measured using instruments such as a range finder, inclinometer, and image analysis. Lennertz et al. (2018) suggest that precise equipment be used by the VO for determining altitude. Lennertz et al. (2018) note that it would be possible for an operator to estimate sUAS altitude when they are aware of the ground distance from the target and the viewing angle of the sUAS. Therefore, Lennertz et al. (2018) recommended that a basic training on altitude estimation could be covered in the Part 107 training for both pilots and operators.

Finally, Lennertz et al. (2018) specify a few limitations in their study. The operator performance was examined against one type of background (clear sky with trees on the horizon). They mention that this background is not complex and that it was easy to maintain visual contact with the UAS. They hypothesize that the altitude estimation may improve when the UAS is viewed against a background that allowed the operator to compare the UAS's altitude to a nearby structure. A more complex environment might be detrimental in maintaining visual contact with the UAS (Crognale, 2009). Another limitation of this study was that only one sUAS, the DJI Phantom 4 Pro, was utilized. This is a sophisticated UAS with easy-to-use controls. Lennertz et al. (2018) mention that it would be more difficult for the UAS's altitude to be judged if a smaller and less sophisticated sUAS was utilized.

Lennertz et al. (2019) conducted a study to evaluate the viability of sUAS visual detection by a tower controller on an airfield. Lennertz et al. (2019) note that due to the viewing location, communication with multiple nearby aircraft, familiarity with the airfield, available tools, and expertise in visually scanning for traffic, tower controllers may be better equipped to visually detect an sUAS and estimate the distance between aircraft and sUAS than ground observers. Lennertz et al. (2019) referenced van Schaik, Roessingh, Lindqvist, and Fält (2010)'s study where tower controllers were tasked with 31 visual duties, ranging from spotting a large bird (such as a gander) to evaluating whether or not an aircraft's landing lights were turned on. Without binoculars, tower controllers estimated a viewing range of about 1,800 m, or about 5,900 ft, or a little over a mile for a large bird in ideal conditions. Lennertz et al. (2019) also referenced Williams and Gildea (2014); Woo (2017) in the study and notes the limitations of the human visual system, highlighting how difficult it may be for a pilot or VO to maintain visual contact with an sUAS, particularly while it is moving.

In Lennertz et al. (2019)'s study, nine participants (tower controllers) were required to visually recognize an sUAS and issue a traffic advisory to a manned aircraft, and estimate the sUAS's altitude and distance from the manned aircraft. The participants were located on the ground for the purpose of this study. The sUAS hovered above a pre-determined spot on the airfield which was relative to the position of manned aircraft (between 800 and 1,500 ft away from the participant) at an altitude of 175 or 300 ft AGL. This study was conducted at Gardner Municipal Airport, which is a "public, non-towered, single runway, Class G airspace" (p. 6) (Lennertz et al., 2019). In this study, the sUAS used was a DJI Phantom 4 Pro (diagonal rotor span of 14 in) and the manned aircraft used was a Cessna 172 or a Pipe Warrior. The study consisted of three independent variables that included "Position of the sUAS relative to the manned aircraft (crosswind, downwind, or final), altitude of sUAS (175 ft or 300 ft AGL), and number of sUAS (none, one, or two)" (p. 9) (Lennertz et al., 2019). There were a total of eight trials for each participant. Six trials had only one sUAS present, on trial had no sUAS present, and one trial had two sUAS present. The results from this are summarized below.

- <u>sUAS Detection</u>

  The participants identified the sUAS 19 out of 72 times in the airfield's vicinity resulting in a detection rate of 26%. The detection rate did not seem to be affected by the sUAS's distance, but there were too few data points to do a statistical analysis. No participants recognized more than one sUAS when two sUAS were present in the same trial run. On the trial run where sUAS was not present, there were no false detections (e.g., misidentifying a bird as an sUAS) (Lennertz et al., 2019).

  Participants detected an sUAS 19 times; eight times with binoculars, 10 times with natural vision, and once where the experimenter forgot to note whether or not the participant was using binoculars. The number of detections with and without binoculars had no statistically significant difference (Lennertz et al., 2019).

  The sUAS was white, yet out of the 19 times where it was spotted, nine times it was identified as looking to be a light color, three times it was identified as a dark color, and seven times where the color was undetermined due to experimenter error. The color of the background and the contrast between the sUAS and the background affected the perceived shade of the sUAS. In this example, recorded weather data revealed no link between the perceived shade of the sUAS and the sky conditions (Lennertz et al., 2019).

(Lennertz et al., 2019) evaluated the link between the overall number of detected sUAS, age, years of experience working as a tower controller, and years in the tower of the controller, but found no significant impacts. There were also no significant changes in the number of sUAS detected when work status (employed or retired) or 20/20 eyesight (corrected or uncorrected) were taken into account.

- sUAS Altitude Estimation

  Participants calculated sUAS altitudes in a variety of forms, with estimations in relation to manned aircraft translated to AGL based on the altitude at which the manned aircraft flew during all trials. During the pre-experiment briefing, the participants were informed that the manned aircraft would be flying at 1,000 ft AGL. The average altitude estimate of the sUAS was 632 ft higher than the actual altitude of the sUAS, indicating that participants overestimated the altitude of the sUAS. On the crosswind run, the smallest altitude inaccuracy was 125 ft with an estimate of 300 ft, while the sUAS was actually at 175 ft. On the downwind section, the biggest height mistake was the 3,000 ft sUAS estimate when it was actually at 2,700 ft. Two of the three participants with Part 107 knowledge gave altitude estimates above 400 ft AGL, despite the fact that sUAS are not allowed to fly above 400 ft AGL according to Part 107 regulations. The study concluded that there were no links between the altitude estimations of participants and their age, or years as a tower controller, or years working in the tower (Lennertz et al., 2019).

- sUAS Position Estimation

  The participants' location estimates were nearly accurate only four times and inaccurate fifteen times. Whether the observation was generally accurate or inaccurate was statistically significant. The participants assumed the sUAS was even further away from the airport than the manned aircraft most of the time, while in fact the sUAS was at least 1,900 ft closer to the airport than the manned aircraft. The participants mistook the sUAS for being on the wrong side of the aircraft or in front of it eleven times due to incorrect estimation of the aircraft position. The estimate was just slightly wrong four times, in which the participants used the airport as reference rather than the manned aircraft. (Lennertz et al., 2019).

- sUAS Distance Estimation

  Out of the 19 trials, a distance estimate was not provided by the participants in two trials. The participants misjudged how far away the sUAS was in the majority of the other 17 trials. The distance between the sUAS and the airport was overestimated 100% of the time by the eight participants who used the airport as a reference. The nine participants that used the manned aircraft as a reference overestimated the distance between the sUAS and the aircraft 56% of the time (Lennertz et al., 2019).

- Confidence Rating

  The participants rated their confidence in detecting the UAS on a scale from one to ten. The participant's median score where the sUAS was detected during the 19 trials was eight out of ten. The participant's median score for locating and estimating the altitude of the sUAS was eight out of ten; the participant's median score for estimating the distance of sUAS was seven out of ten. Participants were somewhat more confident in the UAS's position and altitude in relation to the manned aircraft, but significantly less sure about the distance (Lennertz et al., 2019).

- Strategies and Factors Influencing sUAS Detection

  Participants described many strategies for identifying the sUAS and, if detected, estimating its location, distance, and altitude relative to the manned aircraft in the post-experiment questionnaire.

  The strategies used by the participants for detecting the UAS as described in (p. 19-20) (Lennertz et al., 2019) included "Scanning the surroundings; Using Binoculars; Visual References; Looking for movement or light; Tracking the movement of the manned aircraft."

  The strategies used by the participants for estimating the location of the UAS as described in (p. 20) (Lennertz et al., 2019) included using "Altitude of the manned aircraft; Compass points; Relative clock position of the aircraft; Geography or Landmarks; Scanning from the horizon up to the manned aircraft."

  The strategies used by the participants for estimating the distance of the UAS as described in (p. 20) (Lennertz et al., 2019) included "Using the manned aircraft's traffic pattern; Comparison to size of a bird; Past experience; A reference distance."

  The strategies used by the participants for estimating the distance of the UAS as described in (p. 20) (Lennertz et al., 2019) included using "The relative altitude of the manned aircraft; Knowledge of FAA regulation regarding UAS operations."

  The ability to identify the sUAS was influenced by a number of factors, including the location of the controller/participant on the ground rather than in a tower, prior knowledge of past sUAS activity, and the size of the sUAS (Lennertz et al., 2019).

- Difficulty of the Task and Workload

  The results indicated that four out of nine participants evaluated the assignment as "difficult", four as "moderate", and one participant commented that providing orders to the piloted aircraft was "difficult" but scanning for traffic was "easy" (Lennertz et al., 2019).

Lennertz et al. (2019) note from their study that when the UAS was at an altitude of 175 ft, participants were more likely to detect it, instead of when the UAS was at an altitude of 300 ft. Due to the small number of observations, this difference was not statistically significant. When compared to detection of UAS during crosswind condition, participants noticed the UAS somewhat more often on downwind and final conditions. This might be attributed to the controller's location in relation to the aircraft's flight path, the sun's direction (which was normally southerly, similar to the controller's crosswind sUAS), or the length of time the aircraft stayed at each leg – again, this discovery was not statistically significant.

Lennertz et al. (2019) note that participants provided inaccurate UAS position. Similar to past research, the participants overestimated the UAS's altitude (Lennertz et al., 2018; Loffi, Wallace, Jacob, & Dunlap, 2016). Lennertz et al. (2019) found that participants also overestimated the distance between sUAS and manned aircraft. This overestimated distance when conveyed to manned aircraft pilots could result in the manned aircraft pilot actually having less time to react to the sUAS (Lennertz et al., 2019). Participants were confident or very certain that they had seen all UAS traffic in the area when a UAS was visually detected; however, no participant reported seeing two UAS (when two UAS were present). In terms of both identifying the UAS and giving traffic information, there was a discrepancy between how well participants felt they did and how well they actually did. Lennertz et al. (2019) conclude that the data of this study coupled with past research indicate that tower controllers are unable to successfully detect an sUAS operating in their airspace, even when the workload is low, and the controllers are aware that a UAS is present.

Lennertz et al. (2019) note that one of the limitations in this study was that it was conducted in VMC during daylight hours with variable cloud cover, which might have affected visual detection of the UAS. The other limitation of this study was that tower controllers were not located in the tower, instead the tower controllers were located on the ground. Depending on where the tower controller is located, the background against which the UAS is viewed changes. However, tinted windows on the tower would lessen contrast and make detection more difficult (Lennertz et al., 2019).

Lennertz et al. (2019) conclude from their study that in the unlikely event that the UAS was detected, the controller’s communication to the manned aircraft pilot about the UAS may be incorrect. The false communication may give the pilot an incorrect impression that there is more time to visually detect the UAS and maneuver. Given the diversity in UAS operations and the effectiveness of the human visual system (Williams & Gildea, 2014), Lennertz et al. (2019) mention that training is unlikely to have a significant impact on performance. They recommend that additional solutions such as those that limit the airspace for UAS operating near an airfield (geofencing) or provision of an indicator of UAS operations to the controller that does not rely on human visual detection, would be required.

Wallace, Kiernan, et al. (2019) claim that object recognition is influenced by the observer's visual acuity in addition to relative size. Wallace, Kiernan, et al. (2019), from their analysis of sUAS telemetry data recorded by a DJI AeroScope near an urban airport, mention that 60.1% of UAS have been flown at fewer than 10° visual inclinations from the normal human eye level of 5.75 ft. Based on this finding, Wallace, Kiernan, et al. (2019) suggest that operators preferred to fly longer lateral distances than vertical distances. Therefore, the vast majority of sUAS pilots were unlikely to encounter a perceptual illusion that could occur when an sUAS is viewed at higher inclination angles, as seen in Vance et al. (2017)’s study (Wallace, Kiernan, et al. (2019).

Li, Jia, Peng, and Gang (2019) conducted a study in which a DJI Phantom 4 quadcopter was utilized in a field test to measure the LOS. LOS is defined as the farthest distance between an operator and a UAV at which the operator may visually capture the UAV without employing cameras, telescopes, or other visual aids (Civil Aeronautics Administration, 2018). Thirty-two participants were used in the study and they were required to answer a questionnaire on whether they could see the sUA (response: one – definitely yes, two – probably yes, three – not sure, four – probably no, and five – definitely no) and whether they could hear the sUA (response: one – heard clearly, two – heard somewhat clearly, three – heard indistinctly, and four – did not hear). This study found that the probability of visually detecting a quadcopter that is located 500 m away from the operator, was less than 10%. This study found the LOS distance for the DJI Phantom 4 quadcopter to be approximately 245 m and the corresponding visual angle to be 0.065°, assuming a 50% likelihood of visual capture and the "Definitely or Probably Yes" (DPY) criterion.

Li, Chang, Peng, and Zhao (2019) utilized a DJI Phantom 4 quadcopter to determine the ability of human observers to detect an sUA trespassing into a test field. The authors recruited 20 observers (14 males, 6 females) in their study. The mean corrected visual acuity of the observers was 0.9. The study was conducted in the morning. The weather and visibility conditions at the time of the study were favorable with clear sky, sunshine and light breeze. In the test field, a borderline was defined in the shape of an arc. A trespass was defined to occur when the sUA would cross the borderline and enter the test field. Three directions, along which the sUA was placed, were selected within a sector of 30° from the origin. The origin, where the observers were located, was defined to be 154 m away from the borderline. A total of 48 positions of the sUA, 16 in each direction, were selected in the study. The positions varied in distance to the borderline (20 m and 40 m inside and outside the test field) and altitude from the ground (20 m, 40 m, 60 m and 80 m). Conditional probabilities for the 960 sUA detections were calculated in terms of hit rates (correct identification of a trespass), false alarm rates (incorrect identification of a trespass) and correct rejection rates (correct identification of a non-trespass). In case of hit rates, the probabilities of detecting a trespass for the "Definitely Yes" (DY) criterion were in between 0.22 to 0.67, while the probabilities for the DPY criterion were all greater than 0.67. In case of false alarm rates, the probabilities for the DY criterion were in between 0.02 to 0.13, while the probabilities for the DPY criterion were in between 0.12 to 0.42. In case of correct rejection rates, the probabilities of detecting a trespass for the "definitely or probably no" criterion were in between 0.53 to 0.78. The results showed no clear trends in the calculated probabilities as a function of the altitude or distance of the sUA.

Li, Sun, and Li (2020) conducted a study to determine a sUA's LOS distance and visual angle. They used 24 novice participants (12 male and 12 female) to determine a sUA's LOS distance and visual angle. The participants were required to observe the sUA, a DJI Mavic air: 6.4 cm height, 34.7 cm diagonal length without protectors, and 38.7 cm diagonal length with protectors. The study was conducted during daytime, where the cloudy sky served as the backdrop for the sUA's hovering locations. Li et al. (2020) made the following observations based on results obtained from 384 trials (combination of 24 participants, eight locations, and two modes):

> When the protector was used, the probabilities of visual detection for the DY criterion were lower than those of the DPY criterion between the distance of 155 m and 452 m. Beyond 452 m, the probabilities of visual detection employing the two criteria coincided. The probabilities of visual catch for the DY criterion over all locations (0.29) was significantly lower than that of the DPY criterion (0.47). (p. 5).
>
> When there was no protector, the probabilities of visual catch using the DY criterion were lower than those of the DPY criterion for all the distance. The probability of visual catch for the DY criterion averaged over all locations (0.29) was significantly lower than that of the DPY criterion (0.44). (p. 5-6).
>
> The estimated sUA distances for a 50% probability of visual catching employing the DY and DPY criteria for the Mavic Air flying without the protector were 228 m and 307 m, respectively. The visual angles corresponding to these sUA distances were 0.087° and 0.065°, respectively. (p. 8).

> When the Mavic Air was flying with the protector, none of the participants could hear the sound of the sUA when the horizontal distance was beyond 200 m at an altitude of 40 m AGL. When the sUA was at 150 m away, only one participant out of 24 heard the sUA indistinctly and all others could not hear at all. When this sUA was flying without the protector, only two of the participants could hear the sUA indistinctly at the horizontal distance of 150 m and only one participant could hear indistinctly the sound at a horizontal distance of 250 m. None of the participants could hear when the sUA was 250 m or farther. (p. 8).

This study found the LOS distance for the DJI Mavic Air without a protector to be 307 m and the corresponding visual angle to be 0.065° with the DPY criterion. With the DY criterion the LOS distance was 228 m and the corresponding visual angle was 0.087°.

Li et al. (2020) found contradicting results from K.W. Li et al. (2019)'s study, the smaller Mavic Air (diagonal size of 34.7 cm) that was utilized in this study had a higher LOS distance than the larger Phantom 4 (diagonal size of 59 cm) used in the K.W. Li et al. (2019)'s study. Li et al. (2020) mention that the contradiction might be due to the different colors of the sUA and different contrast of background in both the studies. Li et al. (2020) note that even though the LOS distances from this study were significantly higher than the LOS distances of K.W. Li et al. (2019)'s study, the differences in LOS visual angles were insignificant.

A spinning propeller which would cause blurring of the propeller boundaries without a protector, did not affect the visual angle calculations in this study. The use of protectors did not significantly alter the visual detection probabilities. Therefore, Li et al. (2020) note that their study validates calculation of the visual angle using the propeller diagonal size.

Dunn et al. (2020) researched the success of audiovisual cueing effect on the manual flying performance of remote pilots. Dunn et al. (2020) noted in their literature review that remote pilots face unique obstacles due to limited visual, auditory, somatic, vestibular, proprioceptive, and olfactory sensory inputs compared to typical pilots of aircraft, such as planes and helicopters, due to the nature of UAS (Drury & Scott, 2008; Hobbs & Lyall, 2016). Studies have shown that while often beneficial, audio cues can be missed in the presence of background noise (Baldwin et al., 2012). Multimodal cueing has been demonstrated to be beneficial under high work load since it provides redundant information, should one or more modes be missed (Oskarsson, Eriksson, & Carlander, 2012). Dunn et al. (2020) noted that when paired with visual display information, the usage of spatial auditory systems had the potential to improve spatial awareness of remotely placed UA operators (Simpson, Bolia, & Draper, 2013).

Dunn et al. (2020) compared the effectiveness of visual cueing with auditory and visual cueing on the accuracy and timeliness of pilot manual flight of a sUA. In the study, Dunn et al. (2020) had eighteen pilots perform a navigation task and a spotting task with three visual connections to the sUAS: Visual Line of Sight (VLOS), Beyond Visual Line of Sight using a Monitor (BVLOS-M), and Beyond Visual Line of Sight using Goggles (BVLOS-G). Each visual method was conducted with and without real-time auditory feedback. A final variable in the test was the presence or absence of wind shear to act as a distraction to the remote pilots (RPs). The horizontal and vertical precision of images collected via the sUAS from designated sites and the time taken for the flying task were used to assess remote pilot flying performance. The study utilized a DJI Phantom 4 Professional Obsidian model with propeller guards for the sUA.

The navigational task required pilots to take off and ascend to a height of 2.0 m based on a real-time telemetry display. The pilots were then required to fly through a course of 9 locations in a 3x3 grid with a 4 m spacing. Dunn et al. (2020) found none of the visual connections had a significant impact on the vertical accuracy of the pilots, but did show that BVLOS-M and BVLOS-G both improved horizontal accuracy compared to VLOS. The presence or absence of auditory feedback did not significantly affect the horizontal accuracy. The use of goggles had a detrimental impact on the speed of performance of the task when compared with the monitor and the VLOS (Dunn et al., 2020).

The spotting task required participants to ascend to 2.0 m, proceed directly to a target mat and descend to 0.5 m before reversing the process to return to the starting location. This task was performed with and without wind shear. No impact was seen on horizontal accuracy between the different visual methods, but auditory feedback did improve horizontal accuracy. Wind decreased the accuracy and increased the time required to complete the task. Vertical accuracy was improved by auditory feedback in the presence of wind, but for BVLOS-M without wind it decreased vertical performance. Dunn et al. (2020) posit that the auditory feedback in the absence of wind acted as a distraction to the RPs.

Dunn et al. (2020) concluded that under BVLOS conditions, pilot performance could be improved using a monitor instead of goggles with additional improvements in horizontal accuracy seen with the addition of auditory feedback. When flying using VLOS, Dunn et al. (2020) note that vertical flight performance was improved with auditory feedback.

2.1.3.4 Manned Aircraft Pilots and Safety Observers Performance in UAS Operations

Maddocks and Griffitt (2015) conducted experiments to evaluate the pilot's visibility of sUAS operations close to agricultural applications. Maddocks and Griffitt (2015) evaluated the visibility of an sUAS by pilots flying four fixed-wing aircraft (2 x Cessna T188C; 2 x AT402B) and a helicopter (Robinson R44). The pilots were instructed to fly above five fields and perform a visual survey for obstacles and hazards. Of the five fields, one field contained no hazards, two fields contained a quadrotor sUAS (Agribotix Enduro) and two fields contained ground tarps which were marked to indicate sUAS activity presence. The field test found that even though all the pilots noticed the markings on the ground, only one out of the four fixed-wing pilots spotted the sUAS. The sUAS was only briefly spotted due to reflection from the sun. The helicopter pilot successfully spotted the sUAS in both test fields.

Loffi et al. (2016) conducted a study to establish a predictive UAS platform visibility model benchmark. This benchmark could be used to determine if visual means of UAS detection, identification, possible collision recognition, and evasive response decision-making would be sufficient. Loffi et al. (2016) were motivated by the lack of conclusive support for visual detection of UAS platforms by pilots. They note that Gettinger and Michel (2015), who studied over 900 incidents between UAS platforms and manned aircraft, found that 58.8% encounters happened within five miles of an airport, 90.2% of encounters happened over 400 ft AGL, 21.2% of incidents occurred when the UA-to-aircraft proximity was 50 ft or less, and 8.6% resulted in pilots taking evasive action.

Loffi et al. (2016) tasked 20 participants who were FAA Part 141 collegiate flight program students with visually detecting an sUAS flying at an altitude de-conflicted intercept course with an aircraft in protected airspace during peak daylight hours. The sUAS utilized in the study were a 1.8 ft by 1.8 ft 3D Robotics Iris quadcopter and a Ready Made Remote Control Anaconda fixed-wing UAS with a 6.75 ft wingspan and 4.62 ft length. The results were presented as follows.

- Detectability

  The pilots successfully detected the UAS in 40.3% of the intercepts without a false positive. The quadcopter was detected on 36.8% of possible intercepts and the fixed-wing platform on 87.0% of possible intercepts (Loffi et al., 2016).

- Detection Range

  Pilots detected the quadcopter at less than 0.10 sm on average with the furthest detection at 0.31 sm. The fixed-wing UAS was detected on average at 0.49 sm, with the furthest detection at 1.36 sm (Loffi et al., 2016). Loffi et al. (2016) note that participants did not perform well in detecting the quadcopter, whether hovering or transitioning to horizontal flight, or the fixed-wing aircraft. Further, those participants that performed best in detecting the fixed-wing UAS failed to detect the transitioning quadcopter at an adequate distance (Loffi et al., 2016).

- Pilot Distance Estimation

  Pilots estimated the closest distance between the aircraft and the UAS after each encounter. These estimates ranged from 0 ft (i.e. a collision was imminent) to 1.59 sm. When compared to GPS data, pilots overestimated the distance to the Anaconda fixed-wing UAS by an average of 0.25 sm and underestimated the distance to the Iris quadcopter by an average of 0.20 sm (Loffi et al., 2016).

- Visual Data

  Examination of video from an externally mounted GoPro camera found that the contrast between the UAS and its background contributed to the visibility of the aircraft. Both UAS were difficult to detect due to the visually noisy background (Loffi et al., 2016).

- Qualitative Data

  Qualitative data was obtained from the safety observer's observations and participant's comments. The results found that personal assumptions about the size of the UAS might alter distance perception causing overestimation and underestimation. Several participants stated that the UAS was so close that they thought a crash was imminent which indicates a vertical plane parallax illusion occurring. Most participants erroneously believed they had sufficient time to avoid a collision. Pilots tended to survey the wrong areas for the model, opting to look much lower than the flight path of the UAS. The fixed-wing Anaconda platform was easier to locate, according to participants, than the Iris quadcopter due to the presence of "wing flash" when the Anaconda maneuvered. Sixteen participants noted that the light color of the UAS helped detection, while ten participants remarked detection of birds was an easier task (Loffi et al., 2016).

Loffi et al. (2016) conclude that visual surface area plays a significant role in the detection of an UAS. Small, quadcopter UAS are typically not detected until they are within 0.1 sm. Larger, fixed-wing UAS tend to have a higher detection rate and a mean detection distance approaching 0.5 sm.

Loffi et al. (2016) note that the smaller UAS platform (Iris) detection difficulty is further increased when pilots believe they have more distance and hence more time to react before a potential crash. Loffi et al. (2016) note that “a pilot flying at a cruise speed of 100 kts would likely have adequate time to recognize and respond to a larger fixed-wing platform (Anaconda) compared to a smaller platform (Iris)” (p. 22-23). Loffi et al. (2016) commented that this study represented optimistic visibility conditions that may not be representative of normal NAS operations.

Jacob, Mitchell, Loffi, Vance, and Wallace (2018) conducted a study to determine the average visibility distance of a rotary sUAS fitted with ADS-B to a pilot flying a general aviation aircraft in VMC. This study was a part of the experiments conducted in study. For the Automatic Dependent Surveillance-Broadcast (ADS-B) test, pilots were required to detect a DJI m100 equipped with a uAvionix ADS-B system and white strobe lights on the top. A total of 49 intercepts were performed. Jacob et al. (2018) found that “for the ADS-B flights performed with the DJI m100, the detection rates were low at 7.7%” (p. 754). The minimum detection range was 0.15 sm and the maximum detection range was 1.33 sm. Jacob et al. (2018) mention that “even though the strobe light exceeded nighttime UAS operation requirements by the FAA, they were ineffective during the day” (p. 754). According to Jacob et al. (2018), the presence of ADS-B increased the probability of detecting the UA, compared to the probability of detection without ADS-B. Jacob et al. (2018) mention that while ADS-B enables pilots to be aware of the presence of an UA, it does not ensure visibility of the UA. Jacob et al. (2018) also mention that as the ADS-B technology evolves and is verified to provide reliable and accurate positions of UAs, this technology would be sufficient to aid pilots in maneuvering a UA out of a collision path in time.

Wallace, Vance, et al. (2019) conducted a study to assess the visual detection capabilities of manned aircraft pilots in recognizing and avoiding potential collision conflicts with sUAS during approach and landing. Kephart and Braasch (2010); Wallace, Vance, et al. (2019) Kephart and Braasch (2010); Wallace, Vance, et al. (2019) in their study determined the mean visual detection distances for an sUAS by a pilot performing a visual landing. The study utilized 10, FAA Part 141 pilots to detect a white DJI Phantom 4.

Wallace, Vance, et al. (2019) reported that the overall detection rate of the sUAS in their study was 30%. While moving sUAS were detected at a rate of 50%, static sUAS were detected only at a rate of 13.6%. The mean detection distance for all valid trials was 1,382 ft. For moving sUAS, the mean detection distance was 1,593 ft and was significantly higher than the static sUAS mean detection distance of 747 ft. Based on this observations, Wallace, Vance, et al. (2019) conclude that “moving sUAS are easier to spot than static ones” (p. 23).

Wallace, Vance, et al. (2019) note that in case of static sUAS intercepts, “detections were slightly higher when the sUAS was positioned on the port side of the aircraft” (p. 15). Wallace, Vance, et al. (2019) reason that since the participants were located on the left seat of the manned aircraft, this observation made logical sense. However, this observation is based on only 3 successful detections out of 22 trials.

Wallace, Vance, et al. (2019) mention the creation of an optical illusion through analysis of images of the intercepts obtained from the ground perspective. Based on this analysis, Wallace, Vance, et al. (2019) mention that as the sUAS gets closer to the manned aircraft, it appears even closer in altitude and distance than in reality. This is likely due to the sUAS and the aircraft seen in a direct visual line based on the ground observer's visual angle. A similar optical illusion was reported in Vance et al. (2017)'s study.

According to Wallace, Vance, et al. (2019), the factors that affect sUAS visual detection by manned aircraft pilots include sUAS motion, contrast of sUAS against the background, employment of vigilant scanning techniques, and scanning using the peripheral field of view.

Wallace, Vance, et al. (2019) note that based on the detection distances identified in this study, and a high closure rate, it is highly unlikely that the manned aircraft pilots will have sufficient time to perform evasive maneuvers. Furthermore, in a landing environment, performing evasive maneuvers could be detrimental to flight safety. For the static sUAS trial, Wallace, Vance, et al. (2019) calculated the response time available to perform evasive maneuvers to be about 14.5 seconds (only 2 seconds more than the minimum response time recommended by FAA).

Loffi et al. (2021) conducted a study that evaluated the efficiency of in-flight pilot visual recognition of sUAS platforms encountered during the flight's landing phase in nighttime VMC Loffi et al. (2021)Loffi et al. (2021)Loffi et al. (2021). Loffi et al. (2021) examined if a strobe equipped small UAS flying near an airport approach path could be easily identified and visually distinguished from airport approach lighting systems, and if a pilot could avoid a potential midair collision. Ten participants (piloting a Cessna C-172/S) were required to perform an instrument landing system approach to Runway 17 of the Stillwater Regional Airport, Oklahoma. All sUAS flights were conducted at approximately 137 ft AGL. Participants were directed to begin a go-around maneuver after detecting the sUAS (white DJI Phantom 4) that moved along the approach route.

The results from this study indicated that 12 of the possible 40 passes were used to spot the sUAS, resulting in a 30% success rate. Loffi et al. (2021) also found that participants were equally successful in spotting both moving and hovering sUAS. Moving sUAS had an average detection range of 2,555.8 ft and a median of 2,579.5 ft. The hovering sUAS had an average detection range of 1,705.8 ft and a median of 1,474 ft. Loffi et al. (2021) concluded from this observation that a moving UAS can be detected at a further distance compared to stationary sUAS.

Loffi et al. (2021) mention that the lighting of the airport and approach lighting systems orientation caused the sUAS to be detected slightly more when it was on the starboard side of the aircraft than when it was on the port side. Loffi et al. (2021) noted that one explanation for port side targets having a poorer spotting rate is that they are camouflaged or lost in the powerful four-light precision approach path indicator lighting while having improved visibility on the starboard side due to the absence of ambient lighting, approach lighting, or other lighting sources.

Loffi et al. (2021) mention that while 70% of the participants distinguished the sUAS lighting from the airport's lighting or approach lighting systems, 30% of the participants experienced difficulty making the distinction. Loffi et al. (2021) attributed this high success rate to the participants having fore knowledge of the experiment's purpose. Loffi et al. (2021) comment that further research is required as pilots would be less likely to discern a UAS from lighting (background lighting, airport lighting, or approach lighting) under normal flight conditions during nighttime.

In 75% of successful sUAS sightings (nine out of 12), participants reported distance estimates, with seven of the nine recorded estimations underestimating the true distance to the sUAS by an average of 883 ft and a median of 940 ft. Only 50% of successful UAS sightings (six out of the 12 successful sightings) gave pilots enough time to initiate evasive action to avoid a collision, and 25% of successful sightings occurred after the aircraft passed the UAS position. . Loffi et al. (2021) concluded that pilots are unlikely to successfully perform an evasive maneuver under normal flying conditions during nighttime, especially when the pilots utilize a faster moving aircraft.

2.1.4 Spatial Disorientation and Visual Illusions

Spatial orientation in flight refers to an awareness of the altitude and spatial position of the aircraft relative to the external frame of reference provided by the flat surface of the earth and the gravitational vertical (Stott, 2013). Thus, disorientation can occur when there is a discrepancy between one's sense of position and motion relative to the earth and can be caused by inaccurate visual or vestibular cues and is the single most common cause of human-related aircraft accidents (Heinle & Ercoline, 2003).

Disorientation is presented to a pilot in one of two ways: either by a sense of confusion about the altitude of the aircraft due to deteriorating visual information or conflicting sensations, or the sensations feel correct until the realization that the aircraft is not at the altitude it was intended to be at though self-realization or aircraft alerts. On the other hand, visual illusions result from inconsistencies between the actual visual cues presented and perceived visual cues by the pilot. The visual cues provide pilots with information about distance, speed, and depth of objects, including the comparative size and shape of objects at various distances, an object's relative velocity, and differences in aerial perspective. The following sections detail the potential illusions pilots may experience in flight and the visual illusions that lead to spatial disorientation.

The FAA identified two main categories of illusions: illusions that lead to spatial disorientation and illusions that lead to landing errors. The various motions, forces, and visual cues in flight can create illusions of position and motion; the result is spatial disorientation and may be preventable by looking at a reliable fixed point on the flight instruments or a point on the ground. However, pilots can suffer an illusion but remain spatially aware; thus, it is imperative that pilots be trained on the types of illusions that may occur, how to recognize when they are suffering from an illusion, and how to regain spatial orientation. The first of the illusions that lead to spatial disorientation is the leans, which are abrupt corrections of a banked attitude, when it has been entered into too slowly to stimulate the motion sensing system in the inner ear creating the illusion of banking in the opposite direction.

The Coriolis illusion occurs when there is an abrupt head movement in a prolonged constant-rate turn that has ceased stimulating the motion sensing system and can create the illusion of a rotation or movement in a different axis (FAA, 2021). To minimize the risk of Coriolis illusions, pilots should refrain from making sudden, extreme head movements while making prolonged constant-rate turns. A graveyard spin occurs when a proper recovery from a spin does not stimulate the sense and creates the illusion that you are spinning in the opposite direction. A graveyard spiral may occur when an observed loss of altitude during a constant rate turn creates the illusion of being in a descent with the wings level (FAA, 2021). If a pilot succumbs to a graveyard spiral illusion, they may pull back on the controls, tightening the spiral and increase the loss of altitude. Additionally, inversion illusions result from the abrupt change from climb to straight and level flight, which makes it appear that the aircraft is tumbling backward. A somatogravic illusion may occur because of the rapid acceleration during takeoff, making it appear as if the aircraft is in a nose-up attitude. A pilot may react to this illusion by pushing the aircraft into a dive attitude.

Elevator illusions result from an abrupt upward vertical acceleration creating the illusion of being in a climb. Conversely, the elevator illusion can occur if there is an abrupt downward vertical acceleration, the illusion of being in a descent. The illusion of a false horizon can occur under multiple conditions; when there are sloping cloud formations, an obscured horizon, a dark scene spread with ground lights and stars, or when certain geometric patterns of ground light create the illusion of not being aligned correctly with the actual horizon (FAA, 2021). The last of the illusions that lead to spatial disorientation is autokinesis, caused by staring at a single light for an extended period, and the light source appears to move. To mitigate this illusion, pilots should maintain a visual scan pattern, focus their eyes at varying distances, and minimize their time spent starting at a single object or light source.

The second of the FAA's categories for illusions are illusions that lead to landing errors, which are caused by the varying surface features and atmospheric conditions encountered during the final approach and landing, making the aircraft appear to be at an incorrect height above and distance from the runway. For example, runway width illusions occur when the runway is narrower or wider than usual; for example, a narrower-than-usual runway may create the illusion that the aircraft is at a higher altitude than it is. Runway and terrain slopes illusions can occur when there is an upsloping, upsloping terrain, or both; the upsloping creates the illusion that the aircraft is higher than it is. The opposite is true as well; a down-sloping runway, down-sloping terrain, or a combination of both can create the illusion that the aircraft is at a lower altitude than it is.

A featureless terrain illusion results when an absence of ground features makes the aircraft appear to be at a higher altitude than it is. Absent ground features could be darkened areas, landing over water, or areas that appear featureless because of snow. Various atmospheric conditions can create atmospheric illusions; rain on the windscreen can create the illusion of a greater height, atmospheric haze creates the illusion of being at a greater distance from the runway, and fog can create the illusion of pitching up (FAA, 2021). Lastly, the various ground lighting configurations can lead to ground lighting illusions. For example, lights in a straight line, as you would see on a road, can be mistaken for runway lights. Additionally, if bright lighting systems are surrounding the runway that illuminates the surrounding terrain, it may appear that there is less distance between the aircraft and the runway than there is. The FAA has provided information on training for visual illusions and spatial disorientation and coping mechanisms for when you experience a visual illusion. To personally experience and become accustomed to the warning signs of optical illusions, the FAA recommends using a Barany Chair, a Vertigon, a GYRO, or a Virtual Reality Spatial Disorientation Demonstrator (VRSDD). By experiencing sensory illusions first-hand, pilots are better prepared to recognize a sensory illusion when it happens during flight and to take immediate and appropriate action (FAA, 2020d). To reduce the likelihood of experiencing an optical illusion, pilots should use and rely on flight instruments when flying at night and familiarize themselves with the geographical conditions where the flight will be conducted. When operating a traditional manned aircraft, if a pilot experiences a visual illusion while another pilot is in the aircraft, then the individual experiencing the illusion should transfer control. However, for both manned and unmanned operations, the best way to effectively mitigate the adverse effects visual illusions may have, pilots should be familiar with their aircraft, trust its instruments, have an emergency plan, and rely on their experience.

2.1.5 Non-Visual Means of Detection

Although vision is undoubtedly the primary sensory modality used by the VO to detect incoming aircraft, auditory information also contributes to detection performance. While visual detection requires that the VO fixates their eye gaze near or on the target, hearing is largely omnidirectional, allowing the VO to monitor areas outside of the visual field. This auditory information becomes more useful as the size of the scanning area increases, as the VO can only fixate on a small portion of the scanning area at a time. As one would expect, as the size of the scanning area increases, detection performance decreases. Howell (1957) demonstrated that the detection rage approximately tripled when the observer was given information about the direction of approach. Baldwin (1973) reported a similar finding: detection range went from 2 to 12 km if the ground observer was given information about the direction of approach of the incoming aircraft. Auditory information has the potential to provide direction of approach information to the observer, allowing them to reduce their visual scan area and quickly detect and locate the target. Unfortunately, the literature on the role of auditory information in aircraft detection and tracking is quite sparse.

Several studies have compared auditory and visual detection for ground-based observers. Frederickson et al. (1967) compared auditory and visual detection of incoming B52 aircraft, determining that the mean auditory detection threshold was about 500 m closer than the visual detection threshold. Observers that were farther away from the flight path tended to hear the aircraft before they saw it, while observers close to the flight path demonstrated the opposite pattern. Vance et al. (2017) examined VO performance in a manned aircraft detection task. The target aircraft was a Cessna 172/S model. Subjects heard the aircraft before seeing it in 30.5% of intercepts, saw it before hearing it in 27.1% of intercepts, and heard and saw it simultaneously in 32% of intercepts. In contrast, Li et al. (2020) compared auditory and visual performance when detecting a sUA (Mavic Air). Visual detection always preceded auditory detection. The authors speculate that the noise level of the sUA was low relative to the background noise level, thereby eliminating the possibility of initial auditory detection. While these results might seem to contradict one another, these studies differ from one another to an extent that makes comparisons and general conclusions impossible. The probability of auditory detection is a function of the intensity of the target aircraft relative to the background noise level. The three studies used very different aircraft as the target: a B52 with eight jet engines, a Cessna 172/S, and a sUA. None of these published studies included information about the intensity of the target aircraft or the background noise level, making it difficult to draw any general conclusions. In addition, these studies differed in the size of the area scanned by the observer, which has a direct impact on the utility of auditory information. If the observer is scanning a 360-degree area, for example, auditory detection is likely to occur before visual detection, especially if the incoming aircraft is outside of the visual field of the observer. In general, therefore, the literature supports the conclusion that auditory information is sometimes useful in improving detection performance for ground-based observers.

Moving beyond detection, two studies have examined the performance of observers when estimating the location of an aircraft using only auditory information. (Bauer, 1963) reported that ground-based observers exhibited between 8° and 24° of error when estimating the location of a UH-1B helicopter using only auditory information. (Frederickson et al., 1967) examined the ability of observers to localize and track aircraft using only auditory information. Observers were required to close their eyes and listen for incoming aircraft. Once they detected the aircraft, they moved a pointer to the estimated location at detection and continued to move the pointer as the aircraft continued to move along its flight path. They noted two sources of error in the auditory localization of aircraft. The first arises because sound takes time to travel the distance from the aircraft to the observer. Since the aircraft is a moving object, its actual location changes during that time. Therefore, there is an error due to the difference between the actual and apparent location of the aircraft. The magnitude of this error depends on the speed of the aircraft and its distance from the observer. The second source of error is human error: that is, error related to the difference between the observer's location estimate and the apparent location of the aircraft. This type of error was shown to be relatively small, ranging between 3° and 7° across observers. As sound localization accuracy varies with the frequency content of the sound, additional research is necessary to generalize this result beyond the B52s used in this study.

2.1.6 Team Performance

Teamwork is critical for safe flight operations in the NAS in both occupied and remotely piloted aircraft. Flight crew members can be in proximity of each other as in a multi-piloted cockpit with dual flight controls or separated in the case of VO for UA. However, in both cases, a flight crew team member needs to understand their unique role to the team and interdependencies between team member roles and responsibilities (Delise, Gorman, Brooks, Rentsch, & Stele-Johnson, 2010). In manned aircraft, the pilot's primary responsibility is controlling and monitoring the aircraft flight path (Flight Safety Foundation, 2014). For years, pilot training has taught the first and foremost priority when flying is directing and monitoring the attitude, airspeed, and altitude of the aircraft, hence "aviate" (FAA, 2018). In multi-piloted cockpits, one pilot is identified as Pilot Flying (PF) while the other pilot is identified as Pilot Monitoring (PM). Both the PF and the PM serve unique roles and responsibilities to the flight crew team. In RP operations, the pilot manipulating the flight controls is the PF. Like the PM in manned aircraft, the VO in small unmanned operations serves the specific function of monitoring other air traffic and objects and determining if the UA poses a threat to life or property (FAA, 2020c). The primary responsibility of the VO is communicating safety of flight information to the RP regarding the location, altitude, and direction of flight of the UA and the position of other aircraft or hazards in the airspace. Using the flight-related information, the VO must decide if corrective action is required to avoid endangering the life and property of others (FAA, 2020c). When the role and responsibilities of the VO are defined as part of the flight crew team, individual VO skills become team-based skills associated with situational awareness, problem-solving/decision making, and communication. New training standards are under development for VOs, but it's unclear if the standards include the team-based skills identified (ASTM Standard F3266-18, 2018).

Within the last 60 years, technological advances and enhancements have attempted to increase safety margins within the aviation industry, and aircraft design and automation continue to redefine the human-machine interface. However, until recently, human-factors considerations in aviation focused on the role of the individual instead of the operational and organizational context in an ever-increasing, complex aviation system. Crew Resource Management (CRM) is the application of human factors in today's aviation system (Kanki, Anka, & Chidester, 2019). More specifically, CRM is the improvement of team processes and crew coordination among flight crew members.

According to Kanki et al. (2019), CRM focuses on crew-level aspects of training and operations instead of an individual level. Early on, the aim of CRM was for pilots in command to utilize all available resources, including other flight crew members, to achieve safe and efficient flight operations. Recommendations from the NTSB accident report emphasized the merits of "participative management for captains and assertiveness training for other cockpit crewmembers" (NTSB, 1979). Though initially known as cockpit resource management, CRM became known as crew resource management when aviation teamwork principles were seen to transcend beyond the aircraft flight deck (Helmreich, Merritt, & Wilhelm, 1999). Salas, Fowlkes, Stout, Milanovich, and Prince (1999) listed seven requisite skills for CRM training as communication, decision-making, leadership, situational awareness, mission analysis, assertiveness, and adaptability. By the beginning of the 21st century, new initiatives in human factors research would necessitate five CRM generational shifts and the focus of teamwork in aviation. Teamwork skills for training included communication, briefing, backup behavior, mutual performance monitoring, team leadership, decision making task-related assertiveness, team adaptability, and shared situation awareness (Farago, Shuffler, & Salas, 2019). What started as an attempt to decrease accidents by eliminating human error, moved toward lessening the impact of threats and errors in the aviation environment (Helmreich et al., 1999). According to Martinez, Childes, and Sutliff (2020), the essence of threat and error management is not the elimination of human error but reducing advanced consequences to flight safety through detection and correction.

While team training in aviation and other industries is widely practiced, some still question if the label of CRM is appropriate. According to Havinga, de Boer, Rae, and Dekker (2017), despite studies attempting to show improvements in team performance and safety, the link between CRM training and safety is still unclear. The recent focus in aviation around the world is competency-based training for flight crew training. According to Kearns, Mavin, and Hodge (2016), competency-based training focuses "on what learners need to be able to do in order to perform capably and autonomously in real-world operations" (p.6). Competency is not expert mastery, but the starting point of knowledge, skills, and attitudes for full participation within a given field. Competency-based training and assessment are measured and developed to specified performance standards and contain core competencies that are based on job requirements that describe how to perform a job in a proficient manner (Flin, 2019). In a new era of human resiliency for safety in sociotechnical complex systems, competencies are what make things function properly (Dekker, 2015). Competency-based training is now used in the aviation industry throughout the world for initial and currency training of flight crews, air traffic control, and aircraft maintenance personnel.

2.1.6.1 Situational Awareness

Situational awareness is being aware of your surroundings and using the information around you to predict what it will mean in the future (Hunter, Porter, & Williams, 2020). Human factors researchers highlight situational awareness as one, if not the most, important factor in understanding flight crew decision making (Donnelly, Noyes, & Johnson, 1997; Endsley, 2015; Mosier & Fischer, 2015). (Endsley, 1995) describes the three levels of situational awareness: Level 1 – perception of the elements in the environment; Level 2 – comprehension of the current situation; and Level 3 – projection of future status. Level 3 projection of future status is directly associated with components of resiliency (Martin, 2019). According to (Hunter et al., 2020), Endsley's three-level framework shows how thoughts create feelings, feelings lead to behavior, and behavior, in turn, reinforces thoughts. (Bedny & Meister, 1999)'s two-prong model describes how goals motivate people to action and, if their goals are conflicting, a decision to change course may be initiated. Furthermore, a lack of situational awareness can compromise team performance (Hauland, 2008). Team situational awareness encompasses individual situational awareness because the individual must function as part of the team (Hauland, 2008). Mental models are how individuals perceive an event or set of circumstances and are closely tied to situational awareness. In the team environment, shared mental models allow each member to work toward a shared goal in a dynamic environment (Martinez, 2015; Salas, Sims, & Burke, 2005; Sexton & Helmreich, 1999). Mosier and Fischer (2015) note that coordinated team action requires individuals to have a shared knowledge of the operational environment, standard procedures, practices, and strategies. According to Scheutz, DeLoach, and Adams (2017), "team mental models are critical for making sense of team activities, for understanding the dynamic changes of team goals and team needs …, and for tracking the overall moment-to-moment state of the team" (p. 204). Mental models among flight crewmembers can be a shared understanding of the flight situation or overlapping in the case of individual responsibilities contributing to the flight task (Harris, 2011). Individuals functioning as part of a flight crew team, e.g., VOs, must maintain their individual situational awareness of the flight situation and possess a shared situational awareness with the RP regarding the location, altitude, and direction of flight of the UA and its position relative to other aircraft or hazards in the operating environment.

2.1.6.2 Decision Making and Problem Solving

Closely tied to flight crew situational awareness is flight decision-making. The decision-making process helps predict future decisions and identify possible sources of error, and, therefore, it is closely linked to problem-solving. The Brunswik lens model is composed of the following elements: 1) situation; 2) situational cues; 3) judgment and decision (Rothrock & Yin, 2008). Within this model, the cues that influence the decision maker are presented as the lens through which they see their environment. The interrelationships between the cues show the complexity of the decision-making process (Rothrock & Yin, 2008). Decision ladder models incorporate judgement processes on one leg of the ladder and decision processes on the other and illustrate different ways that operators may skip from one point on the system analysis to the corrective process (Mosier & Fischer, 2015). Classical decision-making, which is based on choices rationally evaluated for the greatest expected utility, may not be best suited for flight crews when complete and reliable information is unavailable and all possible solutions are unclear (Harris, 2011). According to Noyes (2015), naturalistic decision making applies directly to the aviation environment and contains the following key components: 1) assessment of the situation; 2) awareness of the situation (mental representation); 3) knowledge of the appropriate course of action; and 4) awareness of potential consequences of action(s)/inaction. Orasanu (1998) describes situation assessment as the process of defining the problems and risks of the current situation and course of action as the solution that one selects to address problems identified in the situation assessment component. Courses of action are further broken into three types: 1) rule-based (one correct course of action); 2) choice (multiple options that have their respective trade-offs); and 3) creative (not a prescribed course so one must be invented). Similar to naturalistic decision-making, the recognition-primed decision-making model consists of three phases; situation recognition, serial option evaluation, and mental simulation (Simpson, 2001). The first two phases of recognition-primed decision-making align with the model proposed by Orasanu (1998) but add the additional step to encourage evaluation of the current course and constant risk assessment (Simpson, 2001). The integrated decision model suggests that there are three separate paths a flight crew may take to make a decision (Donnelly et al., 1997). According to Noyes (2015), if there is inadequate information or the situation is complex, the flight crew will seek additional information to clarify the representation of the situation. Second, if the flight crew is satisfied with the situation representation, their intention may be to act. The third path is the consequences of the flight crews' actions or nonactions. Mosier and Fischer (2015) suggest a front-end, back-end model for describing decision making. Front-end processes are those which aid in identifying and diagnosing a problem or developing situational awareness, while back-end processes are those that directly contribute to making a decision (Mosier & Fischer, 2015). This framework separates judgement processes from decision-making processes. Endsley (1995) three-level framework for situational awareness describes a decision-making process that demonstrates the connection and overlapping between situational awareness and decision-making. Using Mosier and Fischer (2015) framework, Endsley's first and second levels represent front-end processes as they contribute to the situational awareness of the decision-maker. The third level of Endsley's three-level framework represents a back-end process. In the end, decisions made by flight crews will manifest in communication about go/no-go, options/response selection, procedures, and creative problem-solving.

2.1.6.3 Communication

Effective communication among flight crew members is an essential component of crew coordination (Kanki et al., 2019). According to Martin (2019), communication enables effective situational awareness and decision-making and is key to flight crew resilience. Examples of clear and effective communication among flight crews during critical in-flight situations were prevalent in both the United Airlines flight #232 loss of flight control hydraulic power and the U.S. Airways flight #1549 total loss of thrust. The flight crews in both instances conveyed critical, accurate, and time-sensitive information to each other to successfully manage the aircraft emergency. According to Sexton and Helmreich (1999), a higher word count in the cockpit correlates to a positive increase in performance, while larger words were correlated with a decrease. Salas et al. (2005) found that teams that were more experienced communicate less and, instead, rely on a standard phraseology that allows them to communicate more efficiently. Standard phraseology that is accurate, bold, and concise allows teams to communicate more clearly and perform better. According to Kanki (2019), communication is key to crew coordination and affects flight crew performance in five different ways:

1) Communication conveys information.
2) Communication establishes interpersonal/team relationships.
3) Communication establishes predictable behavior and expectations.
4) Communication maintains attention to task and situational awareness.
5) Communication is a management tool (Kanki, 2019).

Communication continues to be a major component in team training of flight crews and serves as an informational function to problem-solving and decision-making. Initial training for flight crew members focuses on monitoring the other team members' performance and seek, give, and receive task-related feedback (Farago et al., 2019). The crew environment goal is that team members clearly and accurately send and receive information and provide useful feedback. According to

Krieger (2005), shared mindfulness (shared situational awareness) allows flight crews to communicate by actively attending to and responding to information.

2.2 Factors Related to Aircraft Visual Conspicuity

In order to avoid midair collision between aircraft, remote pilots and VOs need to be able to easily detect other aircraft in the vicinity and perform evasive maneuvers when necessary. Many factors influence the detectability of aircraft (both manned and unmanned). The two main factors reviewed in this section are lighting systems and paint schemes. This section describes in detail the literature available on lighting systems used on aircraft to increase conspicuity and the factors that affect the visibility of lights. Additionally, this section reviews the research available on the effectiveness of paint in increasing the visibility of aircraft during the day.

2.2.1 Lighting Systems

Lighting systems in manned aircraft and UA aid the pilot and observers to visually detect and avoid intruder aircraft. Lighting systems are used to make the aircraft more visible to other aircraft and to ground traffic. The increased visibility reduces the chances of collision. The two external lighting systems currently in use on manned aircraft are position lights and anticollision lights.

Position lights, also referred to as navigation lights, are used to help pilots determine the relative position of an aircraft in the air. Position lights also help determine the aircraft heading. 14 CFR § 25.1385 (FAA, 2013b) states that position lights must constitute a red light on the leading edge of the left wingtip, a green light on the leading edge of the right wingtip, and a white color rear light mounted as far aft as possible on the tail. Projector (1962) investigated the characteristics of position lights and their effectiveness in minimizing the risk of collision. The author states that position lights with a minimum intensity of 100 candles in the horizontal plane provide less than 3-mile visibility in marginal conditions during twilight. The author specifies that this intensity of light would have a visual range of 3 miles only in clear atmospheres. However, in minimum Visual Flight Rules (VFR) conditions, the light range would be reduced to 1.33 miles. Additionally, against a slightly brighter background luminance of 100 foot-Lambert (a foot-lambert is a unit of luminance equal to approximately 3.4 candelas/m^2), the visual range would be negligible. Projector (1962) specifies that while steady position lights are useful to observe the bearing of an aircraft at short range, flashing lights have an advantage over steady lights in terms of conspicuity.

Nelson, Hu, Thomas, Jaworski, and Gildea (2020) provide information regarding the effectiveness of position lights on sUAS/UAS. The authors mention that position lights on UAS may be useful in indicating the direction of motion. However, the authors also recognize two factors of concern in using position lights on UAS. The first factor is that the more common UAS constitutes quadcopters that do not have a true front or back and can change their direction of flight abruptly. This will make it hard to track the UAS orientation and bearing. The second factor is that due to the small size of the UAS, the distance of separation of the position's lights on the UAS is small. As the UAS moves away from the observer, the two light signals on either side of the UAS quickly merge into a point source. Therefore, Nelson et al. (2020) conclude that due to these factors and because the human visual system is more sensitive in identifying changes, flashing lights or strobes are more likely to make the UAS more detectable.

The FAA (1971) advisory circular on aircraft position and anticollision light measurements mentions that due to the superiority of flashing lights in attracting attention, these lights are used extensively as signals for warning. The circular specifies the use of rotating, flashing, oscillating, and strobe lights for anticollision lighting on aircraft.

Anticollision lights help increase the visibility of aircraft. They help the pilot detect and avoid other aircraft, thus, aid in preventing a midair collision. The following section investigates the existing literature on anticollision light systems and provides information regarding the requirements for anticollision lights in manned aircraft and rotorcrafts. A review of literature pertaining to the parameters of anticollision lights that affect its visibility to observers on the ground and in the air is also provided. There is a paucity of information on the usefulness of anticollision lighting on UAS. Therefore, literature on the effectiveness of anticollision lights increasing the conspicuity of manned aircraft and rotorcraft is first examined. Following this, a brief review of existing literature with respect to the use of anticollision lights on UAS is provided.

2.2.1.1 Anticollision Light Requirements

The requirements of anticollision lights in aircrafts and rotorcrafts are provided in the CFRs: (14 CFR § 23.1401) (2013a) and (14 CFR § 25.1401) (2011a) for aircrafts, and (14 CFR § 27.1401) (2002) and (14 CFR § 29.1401) (2020a) for rotorcrafts. These regulations provide anticollision lights requirements based on five main characteristics: field of coverage, flashing characteristics, color, light intensity, and minimum effective intensities. The regulations state that the lights should be located such that they will not impair the crew's vision (14 CFR § 23.1401) (2013a). The anticollision light system should illuminate the vital areas around the aircraft, considering the aircraft's physical configuration and its flight characteristics (14 CFR § 25.1401) (2011a). The effective flash frequency defines the flashing characteristics of anticollision lighting on aircraft. When observed from a distance, the effective flash frequency is the frequency seen when considering the aircraft's complete anticollision light system, including any existing overlaps when the system consists of more than one source of light. It applies to all sectors of light, including any overlaps that may exist when the system consists of more than one light source. The regulations specify the use of either aviation red or aviation white for the color of the anticollision lights depending on the category. The minimum effective intensity for anticollision lights used on aircrafts are generally higher than that used on rotorcrafts.

2.2.1.2 Parameters Affecting Visibility of Anticollision Lights

The following section provides a review of the existing literature found regarding various properties of anticollision lights. Details from the literature regarding the human physiological response to properties of anticollision lights that affect visibility are provided. The section contains information regarding the effect of parameters such as flash rate, intensity, color, environmental factors, and field of coverage on the visibility anticollision lights.

In studying the role of anticollision lights in preventing midair collisions, Projector (1962) uses the Blondel-Rey equation to analyze the effectiveness of flash duration for a light with a given luminous energy. The author mentions that from the Blondel-Rey equation, it is evident that short flashes produce higher effective intensity when compared to longer flashes. The author states that at the visual threshold, a flashing light is not distinguishable from steady light since from a distance, steady lights also appear to flash or twinkle. An observer can detect flashing lights near and above the visual threshold quickly, usually by two or three flashes; however, the identification of color near the visual threshold is difficult. Additionally, Projector (1962) refers to the work of

Leibowitz (1955) in identifying that the dark duration between flashes, if the flashes are slow, can be troublesome as the pilots' attention may pass through the region before the flash occurs. In laboratory conditions, Leibowitz (1955) found that a person could detect movement rates of 1 minute of angle per second. However, for flashing lights, the detection thresholds are much larger. Projector (1962) summarizes that in an experiment, Sperling (1961) showed that observers could distinguish between 40, 80, and 160 flashes per minute unless the signal was close to the visual threshold. Projector (1962) also provides information regarding the efficiency of light signals. The author specifies signal efficiency as the efficiency with which the luminous energy is converted to light signals with the required color, intensity, and flash characteristics. The author relates the signal efficiency to flash rate. For a given flash energy, shorter flash durations are more efficient than longer flashes until about $1/50^{th}$ of a second. Past this interval, efficiency does not vary much with flash frequency.

The FAA (1971) advisory circular on aircraft position and anticollision light measurements specifies that the intensity of a light source varies inversely with the square of the distance from the source to the observer. This correlation between the light intensity and distance is referred to as the "inverse square law." The intensity of a light source is determined based on the distance and is expressed in terms of candles (foot candles times the square of the distance. The FAA (1971) circular states that the apparent intensity of a flashing light signal should be the same as that of a steady light signal, also called effective intensity. Airworthiness requirements for anticollision lights specify the use of the Blondel-Rey equation to calculate the effective intensity of a flashing light. The equation utilizes the instantaneous intensity and the time interval between flashes to calculate the effective intensity of a flashing light.

Bauer and Barnes (1967) discuss the requirements of light intensity for visibility based on background illuminance of the atmosphere, the time taken by pilots to react, and the velocity of rotorcrafts. For the object to be visible against high intensity (5,000 foot-Lambert or more) background lighting from distances of a mile or more, Allard's Law is used to relate the illumination at the eye of the observer with the distance and intensity of the source and the transmissivity of the atmosphere. Bauer and Barnes (1967) refer to the suggestion by Howell (1957) that the sighting distances are three times greater under experimental conditions than in real operational conditions due to the additional activities that require a pilot's attention during flight. Additionally, the intensity requirements for anticollision lights also depend on the warning time. Warning time is the time required to detect an aircraft or anticollision light, locate it along the azimuth and elevation, judge the probability of collision, make a decision on avoiding collision, and to conduct the necessary evasive maneuver. Bauer and Barnes (1967) assume that it takes 10 seconds for a Vertical Take-Off and Landing (VTOL) and Vertical/Standard Take-Off and Landing (V/STOL) aircraft to complete an evasive maneuver and estimate a warning time of 15 to 20 seconds for a VTOL and V/STOL aircraft. Considering these factors and using Allard's Law, for a 20 second warning time with the VTOL and V/STOL aircraft traveling at 90 kts velocity, Bauer and Barnes (1967) recommend a light intensity of 4,100 candles for application during the day and 100 candles during the night for a rotorcraft with a maximum speed of 90 kts. However, for rotorcrafts with velocities greater than 90 kts, they recommend higher intensity lights.

Hobbs (1991) provides a typical background luminance obtained from the IES Lighting Handbook (p. 325) in Table 1. The background luminance is provided in terms of candelas per square meter.

Candela is a modern definition of candlepower (also referred to as candle). One candle is approximately equal to one candela (Hobbs, 1991).

Table 1. Typical background luminance during the day Hobbs (1991).

Background	**Candelas per square meter**
Sky background on a clear day	3,000
Sky background on an overcast day	300
Sky background on a very dark day	30
Twilight sky background	3
Clear moonlit night sky background	0.03
Ground background with snow cover on a sunny day	16,000
Ground background on a sunny day	300
Ground background on an overcast day	30 to 100

Hobbs (1991) specifies that for strobe light visibility range of 3 nm on a very dark day, the light needs an effective intensity of around 5000 candelas. The author cites the work by Harris (1987), stating that for full daylight, over 100,000 candelas of effective intensity are required. Hobbs (1991) summarizes the military trials outlined in the U.S. Air Force report by Schmidlapp (1977), containing results from multiple studies conducted by the U.S. military:

- During daylight conditions, the anticollision light systems (strobe lights and rotating beacons) are not effective in preventing a collision.
- During daylight, observers on a hilltop could not detect helicopters equipped with either lights of 1,800, 2,300, and 3,300 candelas of effective intensity or a standard red rotating beacon unless viewed against the ground.
- During the day, aircraft were sighted before the strobe lights. Additionally, the intensity of strobe lights was reduced by half after two years of use.
- Observers could not easily detect towers fitted with strobe lights of 36,000 candelas intensity. The strobes were only visible on very dark days with background illumination of around 30 candelas per square meter.

Hobbs (1991) concludes that while strobe lights allow the aircraft to be more visible in low light conditions and against a terrain, they are not likely to be of use against bright background skies (Graham, 1989; Rowland & Silver, 1972).

Projector (1962) mentions that the signal color plays an important role in determining the efficiency of a signal. White fluorescent lamps have efficiencies up to 75 lumens per watt, and green lamps have an efficiency of 125 lumens per watt. Incandescent lights have a lower efficiency of the range of 10 to 20 lumens per watt. Projector (1962) refers to the work done by (Kinney, 1958; Middleton & Gottfried, 1957) and suggests that the photometric intensity of a red light is greater than that of white or green when viewed from a “practical” threshold of illumination. Projector (1962) defines the practical threshold for illumination as 0.5 mile-candles. Projector (1962) mentions that only cones are involved in sensing light when the eye is light adapted and only rods are involved in sensing light when the eye is dark adapted. For intermediate adaption states of the eye, both rods and cones are used to sense light. Additionally, colors are sensed using cones. Therefore, when the eyes are fully dark adapted, and cones are not being used to sense the light, the eyes are unable to detect differences in color. Projector (1962) states that since complete dark adaptation is seldom achieved in real world applications due to ambient and cockpit lighting, it is unclear as to the role of colors in visual detection.

Bauer and Barnes (1967) provide a review of the literature available on the effect of color of anticollision lights on visibility. They identify that for night conditions, aviation red has excellent transmissivity and relatively low backscatter through aerosols. The color red maintains good constancy over distance and with varying meteorological conditions. For daytime operations, they recommend clear covers with high transmission characteristics pending further investigation.

The FAA (1971) advisory circular on aircraft position and anticollision light measurements states that the visible spectrum of light falls within a small range of wavelengths from around 400 to 750 nm. The sensitivity of the human eye varies within this spectrum, with different wavelengths producing different radiant energy and therefore different perceived brightness. The luminous efficiency of yellow-green light is twice as much as that of red light. This indicates that red light requires a much higher power to be equal in brightness to that of yellow-green light.

Hobbs (1991) provides a brief review of the literature available on the effectiveness of anticollision lights and the colors used. The author mentions that the Bureau of Air Safety Investigation and the NTSB on occasion, recommend the use of white anticollision lights to help prevent collision in daylight. Graham (1989), cited by Hobbs (1991) concluded that during daytime operating conditions, the aircraft lights and colors were not effective in aiding the pilot in aircraft detection. From the work of Rowland and Silver (1972), Hobbs (1991) concluded that during daylight operating conditions, lights offered no practical conspicuity, and that aircraft are more easily spotted than the lights on the aircraft. Hobbs (1991) also found that while strobe lights are ineffective against bright background luminance, they allow the aircraft to be more detectable against the terrain, ground, or low light conditions. Hobbs (1991) discusses the use of red and white lights in anticollision light systems. The author hypothesizes that the use of red light as a warning color in aviation may have come about more due to common practice than because of advantages associated with the color red. Additionally, Hobbs (1991) refers to the work of (Connors, 1975) and states that light filters reduce the intensity of light affecting the conspicuity and concludes that anticollision lights should utilize unfiltered white lights.

Projector (1962) provides information regarding the effect of atmospheric transmissivity and background illumination on the visibility of anticollision lights. The apparent intensity is dependent on the atmospheric transmissivity. The atmosphere also affects the perceived color of signal lights, however, under normal conditions encountered by pilots, the attenuation effects of the atmosphere on the color of the light is low in magnitude (Projector, 1962). Projector (1962) cites the work of Middleton (1958) and summarizes that for atmospheres that are of interest to VFR conditions, longer wavelengths of light have greater transmissivity than shorter wavelengths of light. Citing the works of (Rautyan & Speranskaya, 1974; Stiles, Bennett, & Green, 1937), Projector (1962) states that the apparent relative intensities of red and green lights are marginally affected by the atmospheric transmissivity; however, at threshold illumination, the identification of colors becomes harder with red light having higher transmissivity than green. Projector, Porter, and Cook (1962) conducted an experiment to determine the ability of observers to detect and identify the color of lights through backscatter. From their work, Projector (1962) specifies that the pilot's ability to detect the lights, whether steady or flashing, and its color, red, green, or white, was not affected by the atmospheric backscatter. The author mentions that the backscatter of light in the atmosphere under VFR conditions with daylight visibility of 3 miles does not affect aircraft detection.

The signal attenuation due to distance in a clear atmosphere occurs in accordance with the inverse square law (Projector, 1962). For longer ranges, atmospheric transmissivity plays an important role in the reduction of signal intensity. In order to increase the range of visibility Projector (1962) suggests limiting the VFR conditions to narrower ranges. The author identifies that the threshold illumination is subjective and varies with the observer and the training that an observer has had. Projector (1962) mentions that during night conditions, the threshold illumination is not affected greatly by the variation in background illumination. However, as the background illumination increases above the value of a starlit sky, the threshold for signal illumination increases by 100 times its original value (de Boer, 1951; Knoll, Tousey, & Hulburt, 1946; Middleton, 1958). Projector (1962) provides information regarding the adaptive state of an observer measured in terms of the ability to detect a faint signal. The visual capability of an observer is affected greatly by his adaptive state and can change the detection threshold. Projector (1962) cites the work done by Stiles et al. (1937) and states that the sensitivity to the signal 1 second after the background illumination was turned off was as high as 1,000 times the sensitivity to signal an hour after the observer adapted to the darkness. The ambient luminance inside and outside the cockpit limits how a pilot can perceive signals and can undergo dark adaptation.

Bauer and Barnes (1967) discuss the ability of anticollision lights in highlighting vital areas of a rotorcraft considering its physical configuration and flight characteristics. The authors provide recommendations for the placement of anticollision lights on a rotorcraft for visibility. They state that due to the vertical take-off characteristics of a rotorcraft and the ability for lateral movement, the anticollision light systems in use for fixed-wing aircraft provide minimal protection when used in rotorcrafts. Due to the VTOL nature of a rotorcraft, it is necessary for anticollision lights to provide visibility in the regions directly above and below it with greater intensity. The authors recommend a vertical illumination of at least 615-footcandles from a 4,100 candle source during the day and 15-footcandles of illumination from a 100 candle source during nighttime operations. Furthermore, Bauer and Barnes (1967) recommend the placement of two additional anticollision lights for the illumination of the upper surface and lower surface of the rotorcraft.

2.2.1.3 Anticollision Lights in UAS

The effectiveness of anticollision lighting systems in increasing the detectability of UAS and sUAS is a relatively new subject for investigation. Recently, studies are underway to determine the ability of a pilot on a manned aircraft, and the ability of a VO and RP on the ground, in detecting an sUAS/UAS and conducting an evasive maneuver to avoid a midair collision.

Stark et al. (2015) in their study, proposed adjustments to the current manned aircraft lighting systems in order for it to be more suitable for UAS night flying operations. The authors' proposal was based on tests conducted using a fixed-wing foam UAS fitted with a new lighting system. According to Stark et al. (2015), the new lighting system consisted of "wingtip lights, wing-strip lights, tail lights and launch mechanism lights" (p. 254). The lighting system was designed to serve two purposes: 1) to provide adequate visibility to RP and VO within LOS, and 2) to aid in determination of UAS position and orientation. Stark et al. (2015) used wingtip lights to aid the RP in determination of flight direction and UAS roll. The wingtip lights provided visibility up to 170°. While the wingtip lights consisted of red light for the left wing and green light for the right wing, which is in agreement with the FAA Part 23 regulations, these lights were preferred to be nearly omni-directional, which is in contrast to the FAA Part 23 regulations. Stark et al. (2015) proposed additional underwing lights to improve estimation of the UAS heading. The most effective orientation for the underwing lights as determined in the study was perpendicular to the wing leading edge. Stark et al. (2015) used a white tail light that acted as a beacon to the RP and VO. The secondary purpose of the tail light was to aid in estimation of the UAS pitch. Stark et al. (2015) suggested against using a pulsing tail light as it was found to be distracting to the RP during the tests. According to Stark et al. (2015), although a pulsing light aids in detection of UAS through the peripheral vision, it does not provide useful information to the RP or VO who need to maintain visual contact with the UAS on a regular basis. Stark et al. (2015) recommended discontinuing the use of anticollision lights on UAS that are typically bright and flashing.

Dolgov (2016) conducted an experiment to assess the ability of a VO to detect and maintain VLOS with an sUAS and a manned aircraft and to evaluate the possibility of collision between the manned and UA. The author conducted the experiment in three different background lighting conditions: day (overcast sky with 2,000 to 2,500 lux background light levels), dusk (partly cloudy sky with 150 to 50 lux background light levels), and night (cloudy sky with less than 1 lux background light levels), and two fixed-wing sUAS. During dusk and night operations, lighting systems consisting of steady lights were used on the UA. Dolgov (2016) found that the VO was able to track the sUAS better during dusk and night operations than during daylight operations. The author suggests that the VO was able to track the sUAS better during dusk and night conditions because of the presence of lighting systems and due to the contrast that the lighting systems offered against overcast and dark skies, despite not being optimized for visual detection. However, the study is not conclusive since assessing the effectiveness of lights in aiding visual detection was not the primary goal of the study.

Wallace et al. (2018) studied the effectiveness of strobe lights mounted on a UAS in aiding a pilot on a manned aircraft to detect the UAS under visual meteorological conditions. The investigation measured the effectiveness in terms of the distance from which the pilot on a manned aircraft was able to detect the UAS. It was found that the UAS detection rate was low, with the pilots detecting only 3 of the 39 possible intercepts. The investigation was conducted during the late afternoon, and the authors noted that the majority of the participants commented about the difficulty in detecting the UAS due to sun glare. Additionally, the authors mention that when the UAS was detected, the strobe light mounted on the UAS was not spotted by any of the participants. Wallace et al. (2018) refer to the findings by Projector (1962) and Schmidlapp (1977) regarding the ineffectiveness of anticollision lights during daylight hours and mention that the qualitative data from the investigation suggests that anticollision lighting on UAS is relatively unsuccessful in improving the UAS detectability for collision avoidance during the day.

Nelson et al. (2020) provide a brief review of the existing literature on the placement of lights on an UAS to improve visibility. Nelson et al. (2020) examine existing literature regarding the use of anticollision lights in both manned and UA and provide an assessment of the effectiveness of lighting systems in enhancing the visual detection of UAS. Because of the larger size of manned aircraft compared to UAS's, the manned aircraft can be detected at distances further away than UAS's. Establishing whether the light signal is coming from an aircraft or an UAS will influence the decision-making process of the pilot. Thus, Nelson et al. (2020) recommend using distinctive light features to signal the manned or unmanned nature of an aircraft. Nelson et al. (2020) mention lighting scheme suggestions such as using strobe lights with three rapid flashes of white light or using red, green, blue, and white in place of position lights. To increase the visibility of an UAS in the sky, Nelson et al. (2020) specify using beacons located on the top and bottom of an UAS. Nelson et al. (2020) also refer to the research by Jacob et al. (2018), which suggests that lighting the bottom surface of the UAS during bright sunlight conditions may reduce the conspicuity of the UAS. With respect to the work done by Jacob et al. (2018), Nelson et al. (2020) suggest allowing the operator to control the top and bottom surface lighting on the UAS independently to accommodate different atmospheric conditions.

Nelson et al. (2020) state that the human visual system is more sensitive to identify changes (like flashing lights) rather than steady states. Therefore, a flashing beacon light or strobe lights are more effective at signaling the presence of UAS to pilots. However, the authors mention that research suggests that strobe lighting during daylight conditions has minimal effectiveness in increasing visibility despite being highly effective with dark background luminance (Hobbs, 1991; Projector, 1962; Wallace et al., 2018).

Nelson et al. (2020) indicate that there is a lack of literature on the visibility of colored strobe lights during daytime conditions, and testing colored strobe lights with high background luminance would be valuable (Graham, 1989; Hobbs, 1991; Jacob et al., 2018; Williams & Gildea, 2014).

Nelson et al. (2020) provide insight regarding the power constraints of UAS with respect to lighting systems used for visibility. Lighting should not reduce the payload size and endurance of an UAS. Nelson et al. (2020) suggest that the required lighting system may exceed the reasonable payload and power capabilities of an sUAS. Nelson et al. (2020) state that it is possible to generate up to 600 candelas using 5 mm to 20 mm LEDs with a current draw of less than 1 ampere and smaller, 5 mm to 10 mm LEDs require even lower currents. Nelson et al. (2020) cite the work of Yimin, Alex, and Nadarajah (2007), mentioning that LEDs outperform incandescent lights. LEDs are easier to detect than incandescent lights (Bullough, 2012, 2017). Nelson et al. (2020) state that LED lights can be used to generate the required intensities to meet standard requirements currently used for anticollision lights specified for manned aircraft.

2.2.2 Paint Schemes

Hobbs (1991) suggests that a paint scheme that maximizes the contrast of the aircraft color with its background is more useful in increasing the visibility of the aircraft. However, the contrast of the aircraft against the background also depends on the background luminance. A light-colored aircraft is less visible against a light background on a dark day. However, if the background luminance increases, this will reduce the contrast of the aircraft with the background. The reduction in contrast will in turn reduce the visibility of the aircraft. Considering these factors, Nelson et al. (2020) state that paint on the top surface of the UAS rather than the bottom surface provides a better contrast against the ground. Nelson et al. (2020) mention that in a study on increasing the visibility of helicopters propellers, helicopters with the painted propellers were more detectable than ones without painted (Bynum, Bailey, Crosley, & Nix Jr, 1967; Crosley, Tabak, Braun, & Bailey, 1972).

Nelson et al. (2020) specify that lights can increase an UA's detectability during nighttime conditions, and paint can increase the visibility of an aircraft in situations with higher background illumination (during the day). Based on the observer's location, the background against which an aircraft is being viewed will change. If a VO on the ground is viewing the aircraft, it will be viewed against the sky. However, if the observation is made by a pilot from an aircraft in the sky, the background may be the ground with trees and other lights or snow. Therefore, Nelson et al. (2020) suggest that different colored paint schemes may be required for the top and bottom surfaces of the aircraft. Additionally, the background color for the specific mission should be taken into consideration when designing the paint scheme for UAS (Nelson et al., 2020). The authors state that patterned paint schemes are better at making the aircraft more conspicuous than monochromatic paint schemes (Siegel & Lanterman, 1963). Nelson et al. (2020) state that a recent study by White (2016) suggests using a pattern of white and red-orange paint for the top surface of an aircraft and a combination of black and red-orange color for the bottom surface of the aircraft increases the visibility of the aircraft. Additionally, Nelson et al. (2020) mention that fluorescent paint is more effective than non-fluorescent paint in increasing the conspicuity of an aircraft (Crosley et al., 1972; Fekety, Edewaard, Szubski, Tyrrell, & Moore, 2017; Schieber, Willan, & Schlorholtz, 2006; Siegel & Lanterman, 1963; Siegel & Federman, 1965). Nelson et al. (2020) also suggest that adding reflective strips on larger UAS's may be beneficial in increasing the detectability of the aircraft.

2.3 The Current VO/RP Training Paradigm

Safety is the driver for the use of VO during UAS operations. There is a level of training and experience desired for the VO to safely execute the role, however there are no current "official" requirements for this role by the FAA. An ASTM working group (WK62741) is looking to create a standard for training and equipping VO's of UAS, but this is a work in progress and not a completed one and approved document. In an attempt to explore the established training's performed by different institutions, the research team looked at organizations and groups with established UAS programs. The FAA-approved UAS Test Sites all have mature processes and procedures that are used to support operations. VO training is required by the FAA-approved UAS Flight Test Sites, and other safety-focused schools/groups/organizations. An attempt was made to capture the key elements that make up this training from numerous mature programs. The various institutions have different names for the same basic training, including "Visual Observer Training," "Observer Training," and "VO/Communication Training." With different names, all have the same and associated core elements required to safely perform the support. A review of four different VO training courses was completed. These included the following:

- New Mexico State University's FAA UAS Flight Test Site – established over 20 years ago, one of the 7 FAA- approved UAS Test Sites, and has had VO procedures in place for almost 20 years.
- The Alaska Center for Unmanned Aircraft Systems Integration– University of Alaska Fairbank's FAA UAS Flight Test Site has been an FAA Test Site since 2014.

- Kansas State University – Polytechnic's Applied Aviation Research Center– Established in 2008, and provides UAS training in seven areas, including, sUAS Commercial Remote Pilot Training, UAS Night Operations Training, and UAS Law Enforcement Training.
- Public Safety Unmanned Response Team (PSURT) – The North Central Texas Council of Governments has a good student guide for procedures and training materials with the mission of providing professional Unmanned Aerial System assistance to jurisdictions and Emergency Operations Centers, in support of their response, relief and immediate recovery efforts.

The UAS Test Sites and Kansas State University (KSU) consider their procedure and training materials to be proprietary. The PSURT materials are available online at; https://www.nctcog.org/nctcg/media/Emergency-Preparedness/PSURT-UAS-Visual-Observer-Course-Student-Guide.docx

Tasked with looking at the various VO training done by the Test Sites and beyond, the approach was to look at but not publish any organization's materials or approach. The team tried to be sensitive to proprietary data/information. To address the potential proprietary issues, one member of the research team was given restricted/sole access to the various training materials, and a comparison was made across all these documents and summarized in the sections below.

The goals for training VO are focused on the safety of flight. Currently, VOs are used to assure the separation of UA from other aircraft, the VO scan for traffic, and inform the pilot of an UA when traffic is in the vicinity of the UAS so that its pilot can avoid it (Williams & Gildea, 2014). All of the training materials had common elements for the VO to be the eyes and ears of UAS pilots, detect other aircraft, determine if there is a potential conflict, and provide information to avoid the conflict. The VO's understanding of operations, roles and responsibilities, reporting, and more are essential for safe, efficient, and effective mission operations.

The goal of the reviews of various training materials was to capture a comprehensive approach of materials included and best practices for what needs to be done for VO training. Although the depth of training by subject did vary, and the number of categories covered, all the materials reviewed had central core topic areas such as airspace knowledge, Certificates of Waiver of Authorization (COA) requirements and waivers, FAA requirements, and communication procedures. All trainings also had elements not directly associated with the specific job related to being a VO. These included team orientations, interfacing with wildlife, protection of habitats, and more. These other areas are also included as applicable. The common training topic areas are captured in Table 2.

Table 2. Combined Assessment of Visual Observer Training Topics.

Training Topic	Categories in topic	Other/Supplementary Documents
COA Requirements and Waivers	• COA format and contents and specific to the COA under which operations may be performed. • Observes positioned within cannot operate beyond the visual range of observers. • Operations with external pilot must have an observer to assist in detecting other aircraft. • Observers must always maintain direct communication with pilot. • Observers cannot perform other duties or have other responsibilities. • Any additional restrictions are part of the specific COA requirements. • Any additional restrictions or requirements related to waivers (ex. night operations, operations over people, etc.)	https://www.faa.gov/about/office_org/headquarters_offices/ato/service_units/systemops/aaim/organizations/uas/coa/ (FAA, 2019)
Federal Aviation Requirements (General Knowledge)	• FAR § 91.111 – Operating Near Other Aircraft • FAR § 91.113 – Right of Way Rules • FAR § 91.115 – Right of Way Rules: Water Operations • FAR § 91.119 – Minimum Safe Altitudes • FAR § 91.155 – VFR Weather Minimums • FAR § 91.155 – Basic VFR Weather minimums • FAR § 107.3 – Definitions • FAR § 107.31 – Visual Line of Sight Aircraft Operation	https://www.ecfr.gov/cgi-bin/text-idx?c=ecfr&sid=3efaad1b0a259d4e48f1150a34d1aa77&rgn=div5&view=text&node=14:2.0.1.3.10&idno=14 (2012)

	• FAR § 107.37 – Operation Near Aircraft; Right of Way Rules • FAR § 107.39 – Operation Over Human Beings • FAR § 107.51 – UAS Operating Limits • FAR § 107.17 – Medical Conditions • FAR § 107.23 – Hazardous Operations • FAR § 107.27 – Alcohol and Drugs	
Federal Aviation Requirements (VO Specific)	• FAR § 107.33 – Visual Observer • FAR § 107.33a – Effective Communication • FAR § 107.33b – See the aircraft throughout the flight and accurately determine UAS altitude and direction • FAR § 107.33c – Coordination • Any COA or waiver specific information related to VO's	https://www.ecfr.gov/cgi-bin/text-idx?c=ecfr&sid=3efaad1b0a259d4e48f1150a34d1aa77&rgn=div5&view=text&node=14:2.0.1.3.10&idno=14 (2012)

Airspace Knowledge	• Types of Airspace
	  ○ Class A
	  ○ Class B
	  ○ Class C
	  ○ Class D
	  ○ Class E
	  ○ Class G
	• Airport Specifics
	• Knowledge of Instrument Flight Rules and VFR
	• VFR Traffic
	• Notice to Airmen
	• Temporary Flight Restrictions (TFR's)
		https://www.faa.gov/regulations_policies/handbooks_manuals/aviation/phak/media/17_phak_ch15.pdf (FAA, 2016c)

UAS Part 107 - Operating Limits	• Operating Requirements • Registration • Pilot Certification • UA Certification • FAA DroneZone	https://www.faa.gov/news/fact_sheets/news_story.cfm?newsId=22615 (FAA, 2020b)
Part 101 – Moored Balloons, Kites, Amateur Rockets, Unmanned Free Balloons, and Certain Model Aircraft	• Subpart A – General • Subpart E – Special Rule for Model Aircraft	https://www.ecfr.gov/cgi-bin/text-idx?rgn=div5&node=14:2.0.1.3.15 (2017)

Team Composition and Reporting	• Definition of mission support teams' individual roles and responsibilities
	  ○ Remote Pilot in Command (RPIC)
	  ○ Flight Team (VO, Team Leader, Data Specialist, UAS Landing Zone (LZ) Manager)
	• Defined reporting structure
		https://www.nctcog.org/nctcg/media/Emergency-Preparedness/PSURT-UAS-Visual-Observer-Course-Student-Guide.docx (PSURT, 2020)

Responsibilities for Primary (Inside) Observer	• Deployed at launch/landing site • UAS Tracking • Late-game collision avoidance • External pilot assistance • Interface between VO and other personnel • Interference with non-participants and ground vehicles	
Responsibilities for Secondary (Outside) Observer	• Deployed to perimeter of flight area • Designated sectors • Locate non-participating aircraft • Bearing/rang/altitude/heading	

	• Interference with non-participants and ground vehicles	
Responsibilities for RPIC	• Clearly define the roles and responsibilities for the entire support team • Interference with non-participants and ground vehicles	
VO Placement	• Geography • Spacing of personnel • Handoffs	

Communications	• Hand-held radios
	• Call signs
	• Observer to pilot
	  ○ Aircraft tracking information
	  ○ Maneuver recommendations
	• Pilot to Observer
	  ○ Heads up for inbound traffic
	  ○ No factor aircraft calls
	  ○ Communication Procedures
	• Phraseology
	  ○ Communication standards (phonetic alphabet, figures/numbers, altitudes and flight levels, direction, speed, time)
	  ○ Common/proper phraseology
	  ○ Emergency terminology
	  ○ Sample communications scripts
		https://www.faa.gov/education/educators/activities/elementary/media/Aircraft-Identification.pdf (FAA, 2020d)

Situational Awareness	• Know your directions • Airport traffic patterns and arrival routes • Runway orientations	https://www.faa.gov/regulations_policies/handbooks_manuals/aviation/airplane_ha

	○ Duty runway • May monitor local radio frequency (Universal Communication, UNICOM) for departure and arrival calls	ndbook/media/09_afh_ch7.pdf (FAA, 2016a)
UAS Observer Issues	• Size and orientation of the UAS • Paint schemes and lights • Engine noise (or lack of) • Environmental and terrain effects ○ Sun, clouds, haze, dust ○ Mountains in the background • Accurate altitude and distance estimates for non-participating aircraft	https://www.faa.gov/regulations_policies/advisory_circulars/index.cfm/go/document.information/documentID/22569
Spatial Disorientation	• Spatial Disorientation Definition ○ Visual Illusions ○ Autokinesis ○ Flicker Vertigo ○ False Perceptions ○ False Horizons ○ Lost Horizons ○ Black Hole Syndrome/ Black Hole Approach • PSURT Materials regarding eyes/vision ○ Specifically, "rods" and "cones" • Mesopic vision ○ Fixation and fascination	https://www.faa.gov/pilots/safety/pilotsafetybrochures/media/spatiald.pdf (FAA, 2020d)
Techniques	• Scanning Technique 1 ○ 10-degree sectors though the area of responsibility ○ Horizon to operating altitude	https://www.nctcog.org/nctcg/media/Emergency-Preparedness/PSURT-UAS-Visual-Observer-Course-Student-Guide.docx (PSURT, 2020)

	◦ Engine noise may be the first indication • Scanning Technique 2 ◦ Scan the sky in "6-hour segments", 9 o'clock to 3 o'clock and then back. Rotate 180° and repeat. ◦ Start over and repeat the entire pattern ◦ See page 22 of the PSURT info for a detailed approach to scanning • Compass Use ◦ N, S, E, W not "left" and "right" ◦ Give bearings from our location
Emergency Procedures	• Visual (Loss of visual contact) • Comms • Intruder Aircraft • Emergency landings • Lost C2 link (Loss of UAS Flight Control) • Loss of GPS Position • Battery Level • Loss of UAS Power • Flight Termination • Accident Notification
Practical training/application – demonstrated knowledge and field demonstrations for training	• Shadowing personnel on operations to translate classroom to field operations • Live flight demonstrations to demonstrate distances and observations • A successful test operation where the VO demonstrates their ability to ensure the separation of the UA from other aircraft

	○ Correctly used terminology ○ Saw other aircraft (unmanned or manned) ○ Correctly used radio procedures ○ Correctly articulated the position of the other aircraft
Site Specific Knowledge and Safety Training	• Site specific interactions ○ State and local regulations (as applicable) related to state, municipal, city, tribal, or other regulations ○ Special Government Interest (SGI) in controlled airspace (as applicable) ○ Operations near military training installations (ex. White Sands Missile Range, un-exploded ordinance – leave it alone, reporting, etc.) • Weather Safety ○ Know the symptoms and treatment for the weather-related illnesses below ○ Heat stress, heat rash, heat cramps, heat exhaustion, heat stroke ○ Hypothermia, frostbite, trench foot, chilblains • Animal Safety and Recognition ○ Encounters with predators and what you should do ○ Coyotes/Wolves ○ Bears

	○ Snakes/Spiders ○ Lizards/Scorpions ○ Puma/Mountain Lion ○ Moose
Other	• Air Traffic Control (ATC) Interference • Sterile Cockpit • Operation from a moving vehicle • Operation of multiple UAS • In flight emergencies

VO training is not focused on one specific type of operation. Looking forward, other research areas and tasks under the ASSURE research umbrella will have additional unique aspects to the VO's role, expectations, and responsibilities. Longer-term tie-ins with other FAA ASSURE funded UAS research tasks include operations near airports that the University of Alaska Fairbanks (UAF) is leading and with the University of Alabama Huntsville lead Disaster Preparedness and Response task. Standard VO training will be required for each of these and will also need to include additional specific elements particular to the unique operations or locations.

2.4 The Role of VO/RP in Testing of DAA

An investigation of the roles that the VO and the RP in the testing of DAA systems was conducted. These two roles are generally part of all operations. The desire was to assess if there were any differences or changes in their roles if a DAA system was being tested. DAA system testing involves planned encounters with an intruder aircraft which is more complex than just flight operations that look for and assess random air traffic that may or may not impact the UA flight. Planned encounters require another level of planning and safety to maintain safe separations and for in-flight situational awareness.

All flight testing includes test planning, coordination of assets, defined roles and responsibilities, and much more. There is not one set of published standards for performing testing of Detect and Avoid systems. There are many news articles and reports on the performance of the systems being tested, but these do not cover the actual mechanics of the testing. These published materials cover and focus on the results of the DAA testing and the specific DAA performance. ASTM is working on a set of DAA testing criteria (ASTM WK62741, New Guide for Training and Equipping VO of UAS (VO Endorsement)), but these are currently 'working documents' and are not detailed here because they are in process and not fully approved. It is not known if any specific DAA-related testing is included in this document.

Two references that obliquely address the RP and VO elements related to DAA tested were found and reviewed. "UAS Integration in the NAS: Detect and Avoid Phase 2' (Rorie & Shively, 2018) is a PowerPoint presentation that covers the program structure, test design, and operational environments. Stressed in the materials are "See and Avoid: FAR Sec. 91.113" (2012) and the NASA DAA team contributions related to the following:

- Well clear definition
- Alerting
- Guidance
- Displays
- Reference algorithm
- Significant modeling and simulation

In an attempt to better define DAA Alerting, the team defined a clear set of parameters to bound and relay the information. These included the following:

- Symbol – graphical representation of the situation
- Name – Warning Alert, Corrective Alert, Preventative Alert, Guidance Traffic, or Remaining Traffic
- Pilot Action – specific actions related to each alert type

- DAA Well Clear Criteria – Distance Modification (DMOD) in nm, Horizontal Miss Distance (HMD) in nm, Vertical Threshold (ZTHR) in ft, and modTau in seconds
- Time to Loss of DAA Well Clear – in seconds
- Aural Alert Verbiage – specific call outs for each action

The aural verbiage is the only specific set of interface actions found in this document. It does point to better and more uniform practices that could be used by all for DAA testing.

A second paper, “UAS Integration in the NAS Flight Test 6: Full Mission Results” (Vincent et al., 2020), documents NASA DAA testing. The goal of this research was to test the assumptions of the project’s simulation studies and validate the candidate performance standards. A live flight research event was executed at NASA Armstrong Flight Research Center. “The UAS Integration in the NAS Project Flight Test 6 Full Mission sought to characterize UAS pilot responses to traffic conflicts using a representative Low Severe Weather Avoidance Plan (SWAP) DAA system in an operational NAS environment.”

In application to this review, one statement stands out. “For each encounter, a researcher observer monitored the trajectories of the UAS and the live intruder as well as the alerting and guidance generated during the encounter for anomalies. If the observer or the test director noted a significant change in the flight state of the encounter, it was aborted, and an identical backup encounter was executed.” This speaks to constant interchange among the team that is part of flight operations.

Elements of the ASSURE UAS research task “A18_ A11L.UAS.22 – Small UAS Detect and Avoid Requirements Necessary for Limited Beyond Visual Line of Sight Operations: Separation Requirements and Testing” (referred to as A18) are focused on the separation framework for sUAS well clear, development of testing plans to assess DAA systems, and then flight testing. This research area focuses on issues related to detecting potential threats to remain well clear and avoid collisions. It explores sensors, the data produced from sensors, the management and use of that data, and the operational outcome considered safe and acceptable. A flight test methodology is being developed to test DAA technologies through a series of encounters flown against manned aircraft. This is a research effort in process with detailed results to be published at the end of the effort.

The UAF, the University of North Dakota (UND), and the New Mexico State University (NMSU) are the lead institutions on the A18 effort with support from a few other universities. Within the overall A18 effort, the test architecture, tested systems, aircraft, flight locations, encounter geometries, success criteria, and participants and roles are defined. Also included are the communication plans for flight days. These communication plans are similar to communication plans for other UAS research operations completed by UAF, UND, and NMSU. The plans are general to testing of UAS and not specific toward DAA testing.

In general, when looking at the roles and responsibilities related to communications, the flight operations are overseen and organized by a flight test director in conjunction with Mission Commanders (MCs) for each flight crew. Each flight crew is assigned flight support personnel as determined by the MC. The MC will communicate with the support personnel and the pilot-in-command (PIC) of each flight crew. Flight crews have direct communications with VO. The MC also ensures that each flight crew adheres to the flight plan requirements and monitors conformance.

Each day begins with a briefing to cover plans and safety information for the day's activities. Communication during operations is accomplished in several ways. Primary flight operation communications are via dedicated spectrum handheld radios. Each flight crew and associated VO utilize handheld radios for communication. In addition, cell phones may be used as an auxiliary means of communication as required. Some organizations use Slack for communications as well. VHF radios are used to communicate to ATC and local air traffic as required.

If a UAS incident occurs, the PIC communicates directly with their support personnel, who will communicate with the MC. If any incident happens to any one of the research team members, direct communications to the MC occurs. The MC determines the best course of action for these instances. Specific instructions in case of emergencies are conveyed to the research team during the daily briefings. As noted, none of the established communication lines are specific to DAA testing.

There is a highlight put on the communication and roles of the RP and the VO as part of the mission planning. This is integral to safe operations but not explicitly documented in the published materials. During the mission-specific briefs, there is a discussion about the specific flight profiles. With DAA testing, the focus is usually on UAS to piloted intruder encounters. Some DAA testing also involves UAS to UAS encounters, and for some systems piloted to piloted intruders. This last case is done to safely address safe separations in the encounters. In the planning and the mission briefs, the RP and the VO are made fully aware of the encounters to be run as well as the safe separation of the vehicles that are designed into the test plan and into the individual test cards. Vertical and lateral offsets for safe separation are noted to aid the VOs in their assigned duties.

There are many different encounter geometries for DAA testing that include head-on, overtaking, perpendicular crossing patterns, crossing patterns at angels (commonly called "wagon wheels"), rise into, and descend into encounters. VOs are made aware of each pattern being run during the testing to help orient, view, and judge the encounters. These represent the standard operating procedures for the flight test teams on the A18 effort. They are not explicitly documented specifically for DAA and are applicable to all flight testing conducted by this team.

The A18 effort has focused on testing DAA systems with the generation of Test Plans and Test Cards. There is no current uniform way in which to characterize the roles of the VO/RP in the broader scope of DAA testing. The need for clear VO interfaces seen in this project will positively impact the A18 effort. The test reports from multiple DAA testing efforts have been reviewed, but again focus on the system test results and not the details of the test set up, interfaces, and coordination during the actual testing other than in general terms. The results do not capture the VO training accuracy and detection. In the mission planning and briefings, there is the planning of the encounters in advance of the testing, safe separation at all stages of the mission are considered, the roles are not much different other than all parties are made aware of the known interfaces and crossing which purposely fly aircraft closer to each other, and that the team has knowledge of the test configurations and runs to be completed.

2.5 Extension of the VO/RP Training Paradigm towards EVLOS Operations

To date, there are no standardized training programs for UAS VO; nevertheless, many universities and FAA-approved Test sites provide classroom, computer-based, or hybrid training programs that are specific to or include elements pertaining to VOs. However, some stakeholders and pilots believe that those with previous training, manned aviation pilots, and UAS certified pilots should not need VO-specific training; instead, the reason that pilots and non-pilots should require different training regimens and certification criteria (Dolgov, 2018). For example, in lieu of a standard training program, a refresher course for certified pilots may be beneficial to ensure they are aware of their role as a VO and understand the issues that may arise when scanning the operational area during a LOS operation versus during an EVLOS operation and when their input is needed.

Conversely, a thorough training program may benefit new UAS operators, individuals who have never assisted in a UAS operation, or those who have never performed VO duties. Some stakeholders even believe that a training program should require VOs to pass a classroom/online certification exam (Dolgov, 2018). A hands-on/demonstration exam would be practical for the following three topics that have been identified as essential for VOs to be proficient in to successfully accomplish see-and-avoid duties. VOs must be able to 1) track unmanned and manned aircraft in various lighting and meteorological conditions, 2) the VO must be able to accurately scan the airspace for approaching air traffic and be able to shift visual depth of field, and 3) be able to inform the pilot of approaching aircraft with enough time for the pilot to take appropriate action (Dolgov, 2018).

Thus, a VO training program for EVLOS operations, specifically someone new to UAS operations and the duties required of a VO, should detail the type of operation and what visual aids may be utilized in the operation. Additionally, the training should specify if the VO and the Remote Pilot in Command (RPIC) will be in the same location or separate locations, as this may impact how the crewmembers communicate. If the VO and RPIC are in the same location, they may opt for direct, verbal communication, whereas if they are in separate locations, they will need to use a communication aid such as a radio or phone. Any visual aid that may be utilized during an EVLOS operation, such as binocular or telescopes, should require training as these devices should not be used as the primary means of keeping the surrounding airspace and ground insight but should be supplemented only when needed. Further, training for EVLOS operations may need a section on communication procedures for EVLOS operations if there is more than one VO, to ensure each VO knows when their input is required and to minimize VOs talking over one another. Furthermore, training VO for EVLOS operations should be tailored to their audience, new or experienced operators, and should differentiate between the roles in requirements of the VO during LOS and EVLOS operations.

Furthermore, training on the risk management procedures for identifying the geographical features near the operational airport that may induce visual illusions would be beneficial as the VO in any operation may experience illusions based on the lighting and geographical features nearby. Moreover, increased training should be considered for identifying intruder aircraft in the airspace during adverse conditions that may cause visual illusions to occur, including a sunny day where the VO's vision may be impaired by the sun or a cloudy day where the VO might rely on aircraft lights for identification. This section serves as suggestions to the current VO/RP training that were reviewed from the FAA-approved Test Sites and further research is needed to create standardized VO/RP training.

3 CONCLUSION

The literature review identified the current state of research on VO/RP visual acquisition and avoidance of potential collision hazards. Since the VO/RP performance is directly related to their vision, the research team explored the limitations of the human visual system and human visual performance models, and investigated the role of auditory information on VO/RP performance. The literature review presents the most common type of visual illusions that pilots and observers could experience, and the role of lighting systems and paint schemes that could enhance the aircraft visual conspicuity.

The research team also explored the current state of research on the see and avoid principle. This principle, which relies on the visual detection capabilities of manned aircraft pilots to avoid a potential collision with other traffic, has been studied in aviation for a few decades. While most of the observations noted in the research on the see and avoid principle are not directly related to VO/RP performance, a few of them provide useful insight into effective strategies on visual detection and scanning that could prove beneficial in VO/RP tasks.

The literature review details the current VO/RP training paradigm and briefly discusses extension of the VO/RP training paradigm towards EVLOS operations. The literature review briefly addressed the roles of VO/RP in the testing of DAA systems. Since the primary responsibility of a VO is communicating safety of flight information and information on other aircraft or hazards in the airspace to the RP, the literature review highlights the importance of including team-based skills associated with situational awareness, problem-solving/decision making, and communication in the VO training standards.

3.1 Key Findings

The key findings of the literature review relevant to VO/RP performance are listed below as bullet points. The bullet points are provided for each of the five main sections of the literature review.

1. Human Factors Related to VO/RP Task Performance

Human Visual System Limits

- The human visual system is limited by the following factors: blind spot, acuity threshold, accommodation of the eye, empty field myopia, and focal traps. The human visual system during nighttime is limited by the following factors: mesopic vision, scotopic vision, night blind spot, and dark adaptation.
- Vigilance is an important human factor for visual tasks performed for long durations. Studies have shown that for VO tasks, vigilance decreases after 30 to 60 minutes.
- Factors that affect visual scanning include attention and response to traffic movement, refocusing eyes with and without switching views, eye movement, threat spotting, retinal eccentricity, contrast threshold, small visual angle, visual obstructions, and visual search requirements.
- In order for an aircraft to have a reasonable chance of being visually observed, it must subtend at least 12 minutes of visual arc.
- Detecting and recognizing an invading flying object, assessing its collision potential, making an avoidance decision, and initiating an avoidance maneuver takes a pilot a

minimum of 12.5 seconds, according to the FAA AC 90-48D. Significant caveats must be placed on this metric when considering human performance. The reference AC does not describe encounter geometry used for this timing. The AC provides only a general idea of a reaction time which may not be typical or even conservative. It should also be noted that the AC breaks down the elements into segments, with 5 seconds attributed to the pilot becoming aware of the collision course and 4 seconds in deciding evasive response. This lends itself to the AC's following comment that see and avoid alone is likely insufficient for collision avoidance. If the 12.5 seconds reaction time is used as a human observer performance baseline for DAA compliance means, these caveats should not be ignored.

Human Visual Performance Models

- Human visual performance modeling is complex, and most of the models cannot easily simulate real-world performance in terms of target and background contrast, navigation and artificial lights, size, orientation, visual clutter, and location of the target image on the retina.
- Visual models are useful when designing real-world experiments but are not recommended for VO operations in estimating visual distance accurately.
- The SSO model developed in 2009 can estimate the minimum contrast threshold and the maximum distance threshold of aircraft with varying size, orientation, distance and background.
- A new mathematical model developed in 2020 indicated that sUAS images do not usually become large enough to be viewed by manned aircraft pilots in time to avoid a collision. Therefore, according to this model, the see and avoid principle is not reliable in case of sUAS detection. According to this model, the two most important factors that affect the sUAS detection are the size of the sUAS (positively correlated with detection) and the speed of the manned aircraft (negatively correlated).
- Visibility of the UAS drops to fewer than ten arc-minutes when operated over 400 ft altitude.
- Most sUAS are unlikely to be seen beyond 4,000 ft.

sUAS Visual Detection by VO/RPs

- VOs are poor at estimating the distance and the altitude of the sUAS.
- VOs are likely to overestimate both the distance and the altitude of the sUAS.
- Detection rates and detection distances vary significantly across the studies mentioned in the literature review. Typically, detection distances are higher for larger sUAS due to a larger visible cross-section.
- Size alone cannot predict the visibility of sUAS. Color and background contrast can have major impacts on the visibility of the vehicle.
- Key factors that can hinder the visual detection include the sUAS size, sun position and visual obstructions encountered by VOs.
- In general, the visibility of an aircraft (manned and unmanned) during daytime is determined by its physical size and contrast against the sky and clouds, whereas lighting system determines visibility at night.

- Experience of VOs and corrected vision (20/20) may have a negligible impact on VOs ability to visually detect sUAS.

<u>sUAS Visual Detection by Manned Aircraft Pilots</u>

- Visual surface area of the sUAS plays a significant role in its detection. Therefore, fixed-wing sUAS may be easier to visually detect compared to rotary-wing sUAS.
- sUAS in motion are easier to detect than stationary sUAS.
- Key factors that affect sUAS visual detection by manned aircraft pilots include sUAS motion, contrast of sUAS against the background, employment of vigilant scanning techniques, and scanning using the peripheral field of view.

<u>sUAS Detection during Nighttime</u>

- VOs can maintain VLOS of sUAS better at night and dusk than during the day. In contrast, time of day has a negligible impact on VOs ability to maintain VLOS of manned aircraft.
- sUAS in motion are easier to detect than stationary sUAS for night flights.
- Detection of sUAS at night is significantly impacted by airport and approach lightings systems.
- RPs and VOs should complete a site inspection during the daytime to identify potential visual obstructions that could lead to collisions during nighttime operations.
- RPs and VOs should complete training on determination of UAS orientation using only external UAS lights.
- A secondary VO, who is located at a distance from the RP and can relay information on visual obstacles and intruding air traffic to the RP should be utilized in all night operations.

<u>Ability of VO/RPs to avoid a Potential Collision</u>

- VOs are poor in estimating collision likelihood of UAS with surrounding traffic. There is a significant risk of RPs not having enough time to avoid a collision, as RPs could take longer than the 12.5 second estimate to follow required procedures for initiating collision avoidance.
- VOs perceive a worse collision potential than reality and that VOs overestimate closure rate rather than underestimating it.
- Without audible signals, TCAS, or radio announcements, visual detection by VOs is unlikely to contribute considerably to collision avoidance.
- VOs may be able to contribute considerably to collision avoidance by utilizing trajectory estimation strategies, like tracking of an object projected on a flat plane rather than maintaining a linear optical trajectory.

<u>Ability of Manned Aircraft Pilots to avoid a Potential Collision</u>

- Manned aircraft pilots are unlikely to successfully perform an evasive maneuver from a sUAS under normal flying conditions during both daytime and nighttime, especially when operating a faster-moving aircraft.
- A manned aircraft pilot flying at a cruise speed of 100 kts would likely have time to detect and maneuver away from larger fixed-wing sUAS compared to smaller quadcopter sUAS.

- While ADS-B enables manned aircraft pilots to be aware of the presence of an UA receiving ATC services, it does not ensure visibility of the UA.
- As the ADS-B technology evolves and is verified to provide reliable and accurate positions of UAs, this technology may be sufficient to aid manned aircraft pilots in maneuvering their aircraft out of a collision path with a UA in time.

Role of Visual Aid in sUAS Detection

- There is no difference in detection with and without binoculars of a DJI Phantom 4 Pro sUAS.
- Binoculars and night vision goggles are impractical for anticipating midair collision due to the magnification (binoculars only) and limited viewing angles (both binoculars and night vision goggles).
- Binoculars and night vision goggles reduce the situational awareness of the VO.

Presence of Optical Illusions in sUAS detection studies

- VOs experience strong optical illusions when the aircraft and sUAS are in proximity and either relatively close to or overhead of the VOs.
- The relative distance and collision potential assessments are less accurate when aircraft are approach each other, especially when the aircraft are overhead or when lateral offsets from the observer are small.
- Vertical parallax illusions can cause pilots to believe that sUAS collisions are imminent despite a safe separation distance being maintained.
- As the sUAS gets closer to the occupied aircraft, they appear even closer in altitude and distance than in reality.
- sUAS pilots are unlikely to encounter a perceptual illusion when an sUAS is viewed at higher inclination angles.

Spatial Disorientation and Visual Illusions

- There are two categories of optical illusions; illusions that cause spatial disorientation and illusions that can cause landing errors.
- Pilots can experience illusions but remain spatially aware.
- Spatial disorientation is the single most common cause of human-related aircraft accidents.
- Visual illusions that lead to spatial disorientation can be mitigated by looking at a reliable fixed point on the flight instruments or a point on the ground.

Non-Visual Means of Detection

- Auditory detection of incoming aircraft often precedes visual detection, especially when the aircraft is loud relative to the background noise level.
- Auditory information can provide an initial location estimate that the VO can use to reduce the size of the visual scan area, speeding up visual detection.
- VOs are also able to estimate the location of an aircraft quite accurately using only auditory information.

- More research is needed to determine the signal-to-noise ratios necessary for auditory information to have a significant impact on aircraft detection and tracking by ground-based observers.

Team Performance

- VOs perform a specific role that is team-based during unmanned flight operations.
- Like the role of pilot monitoring in multi-crew manned flight operations, VOs provide backup to the pilot flying/pilot in command.
- 14 CFR § 107.33 identifies effective communication as a requirement among unmanned flight crewmembers.
- ASTM standards for unmanned operations identify the importance of flight crew teamwork and require public safety RPs to demonstrate the ability to communicate clearly, effectively, and accurately.
- Standard phraseology promotes clear and concise communication between flight crewmembers.

2. Factors Related to Aircraft Visual Conspicuity

Lighting Systems

- Lighting systems on aircraft (manned and unmanned) offer a contrast against overcast or dark skies. This enables VOs to more efficiently track an sUAS during dusk and night conditions.
- The ability of a VO/RP to detect anticollision lights is adversely affected by factors such as background illumination, presence of other lights in the background, low level of contrast between the UA equipped with lights and the background, and time required for the human eye to adapt to the dark.
- LED lights can be used as anticollision lights on sUAS to generate the required intensities since they draw less power and have shorter onset times.
- Rotary-wing UAS may experience improvement in visibility and detectability through placement of anticollision lights directly above and below them.
- Position lights, based on current FAA part 23 regulations, may not be useful as a navigation aid for sUAS due to their small size and due to the nature of the flight of UA (without a proper front and back position).
- A pulsing light aids in detection of UAS through the peripheral vision. However, it might not provide useful information to RPs or VOs who need to maintain visual contact with the UAS on a regular basis.
- Anticollision lights on UAS that are typically bright and flashing might be distracting to RPs or VOs.

Paint Schemes

- Certain type of paint schemes may result in an increase in an UA’s conspicuity during daytime. Background color is an important factor in selection of a paint scheme.

- Depending on the placement of the observer (air or ground), different colored paints on the top and bottom surface may aid in increasing contrast and thereby improving UA's conspicuity.
- In general, brighter colored paints (red-orange or white) on the top and darker colored paints (black) result in the largest increase in UA's conspicuity.
- Fluorescent paints provide a greater increase in UA's conspicuity compared to monochromatic paints, especially when used on the top surface of UA.

3. The Current VO/RP Training Paradigm

- There are no standardized training requirements for VO; however, many universities and institutions have their own training guidelines.
- While the number of categories covered and the depth of training by subject did vary, the Test Sites and university materials reviewed had central core topics such as airspace knowledge, COA requirements, waivers, FAA requirements, and communication procedures.
- Many of the reviewed training programs detail topics not specific to VO tasks, such as site-specific information, including state and local regulations, wildlife interactions, and weather safety.
- The top level "Training Topics" included the following:
  - COA Requirements and Waivers
  - Federal Aviation Requirements (General Knowledge)
  - Federal Aviation Requirements (VO Specific)
  - Airspace Knowledge
  - Part 107 - Operating Limits
  - Part 101 – Moored Balloons, Kites, Amateur Rockets, Unmanned Free Balloons, and Certain Model Aircraft
  - Team Composition and Reporting
  - Responsibilities for Primary (Inside) Observer
  - Responsibilities for Secondary (Outside) Observer
  - Responsibilities for RPIC
  - VO Placement
  - Communications
  - Situational Awareness
  - UAS Observer Issues
  - Spatial Disorientation
  - Techniques
  - Emergency Procedures
  - Practical training/application – demonstrated knowledge and field demonstrations for training
  - Site Specific Knowledge and Safety Training
  - Other
- Implementing a demonstration of knowledge or field demonstration such as a successful test operation where the VO demonstrates their ability to ensure the separation of the UA

from other aircraft would be beneficial for determining whether a trainee can perform VO tasks successfully.

4. **The Role of VO/RP in Testing of DAA**

- There is no one set of published standards for performing testing of Detect and Avoid systems.
- There is no current uniform way to characterize the roles of the VO/RP in the broader scope of DAA testing.
- Documented DAA testing results do not capture the VO training accuracy and detection.
- Roles of VO/RP specifically in the testing of DAA systems are not defined formally beyond what is best practice for all flight testing.
- Communication and roles of the RP and the VO are part of the mission planning but not formally documented in the literature.
- DAA testing involves planned encounters with piloted aircraft. During the mission-specific briefs, there is a discussion about the specific flight profiles. RPs and the VOs are made fully aware of the encounters to be run and the safe separation of the vehicles designed into the test plan and into the individual test cards. Vertical and lateral offsets for safe separation are noted to aid the VOs in their assigned duties.
- VOs are made aware of each encounter pattern being run during the testing to help orient, view, and judge the encounters.
- There is an opportunity to improve the interface, interactions, and common verbiage for the VO and the entire flight team.

5. **Extension of the Current VO/RP Training Paradigm**

- Stakeholders and pilots believe certified pilots do not need VO-specific training. Their training regimens should be different as they are experienced in VO tasks related to EVLOS operations.
- VO trainings that identify and differentiate between the VO requirements during a LOS operation and an EVLOS operation are imperative.
- VO training should identify and explain the various communication aids that may be used during an EVLOS operation when the RPIC and VOs may be separate locations, as well as proper communication procedures.

3.2 Key Gaps

There are only a limited number of studies, publicly available, that have been performed to assess the role of VO/RPs in visual detection of sUAS. The number of trials and the number of participants varied significantly across all the studies. In some of the studies, the number of trials or participants was small. When the number of trials or participants is small, it is not possible to extrapolate results of an experiment to all possible sUAS operations not included in the study. Additionally, results of these studies are limited to sUAS platforms of similar size that were used in the study.

In the literature review, experiments related to the see and avoid principle were reviewed. Most of these experiments were conducted more than 20 years ago, at a time when UAS had not even been conceptualized. While some of the qualitative findings of these experiments provide useful information for visual detection of sUAS, the quantitative findings including detection rate and detection range, are not applicable due to the larger size of manned aircraft and the high closure rates.

All research reviewed used limited data sets for the human visual acuity that do not represent the full range of human vision. This adds an additional level of uncertainty to the data obtained from the research since not all humans have the same vision or visual acuity. The researchers did not consider the participants' visual acuity as a variable in their study. In most studies, the participants' visual acuity was reported to be 20/20 or better, with or without correction.

Most of the studies were performed under VMC and during daylight. Only three studies investigated the performance of VOs or manned aircraft pilots to visually detect a sUAS during nighttime (both studies were performed in VMC). A few studies encountered variable cloud cover conditions, which may have affected their findings. Due to these limitations, there are insufficient data points available to establish VO/RP performance in tracking unmanned and manned aircraft in various lighting and meteorological conditions.

Several contradictions exist in the findings of the studies mentioned in the literature review. For example, in one study, binoculars made no difference in the performance of a VO to visually detect a sUAS. In contrast, in another study, binoculars reduced the VO's situational awareness. In a separate example, the LOS distance of a smaller sUAS was greater than that of a larger sUAS. Additional research is necessary to address these kinds of contradictions.

One of the literature review objectives was to identify instances where aircraft conspicuity was challenging or when optical illusions were present. Only three studies mentioned the presence of an optical illusion. Additionally, most of the studies were performed against a simple type of background. A complex background with visual obstructions typically represents a situation where aircraft conspicuity could be challenging. Additional research is needed to generate data points that represent challenging visual conditions for the VOs.

All the studies mentioned in the literature review, except for one, were limited to assessment of VO performance for VLOS operations. There is lack of information regarding VO performance for EVLOS operations.

3.3 Next Steps

The information provided and the key gaps identified in the literature review will be used for planning simulations, tests, demonstrations, and/or analysis needed to assess VO/RP performance and validate related standards.

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