Evaluation of Glare as a Hazard for General Aviation Pilots on Final Approach

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July 2015

Final Report

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Technical Report Documentation Page

1. Report No. DOT/FAA/AM-15/12	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Evaluation of Glare as a Hazard for General Aviation Pilots on Final Approach		5. Report Date July 2015
		6. Performing Organization Code
7. Author(s) Rogers JA,[1] Ho CK,[2] Mead A,[3] Millian A,[3] Beben M,[3] Drechsler G[3]		8. Performing Organization Report No.
9. Performing Organization Name and Address [1]Greensboro College 815 West Market St., Greensboro, NC 27401 [2]Sandia National Laboratories P.O. Box 5800, Albuquerque, NM 87185 [3]Federal Aviation Administration, Civil Aerospace Medical Institute P.O. Box 25082, Oklahoma City, OK 73125		10. Work Unit No. (TRAIS)
		11. Contract or Grant No.
12. Sponsoring Agency name and Address Office of Aerospace Medicine Federal Aviation Administration 800 Independence Ave, S.W. Washington, DC 20591		13. Type of Report and Period Covered
		14. Sponsoring Agency Code
15. Supplemental Notes Work was accomplished under approved task AM-HRR-521		

16. Abstract

   Solar power is a growing source of energy for airports and for their communities. While solar power panels provide a useful means to generate revenue and to provide energy locally, it does pose a potential hazard in the form of glare. In the current study, pilots were exposed to glare during a series of flights in a flight simulator, and their perceived impairment was recorded.

   During the approach phase of each flight, we simulated glare from one of four possible angles (0, 25, 50, and 90 deg left of straight ahead) and for glare durations of either 0 (no glare control), 1, and 5 s. The glare was simulated using halogen lamps that, under the lighting conditions of our lab, approximated the visual effect of solar glare. Subjective measures of impairment were recorded for each condition. There was a significant main effect of glare duration and a significant main effect of glare angle.

   Impairment was perceived as being worse for glare sources that are straight ahead of the pilot and of longer duration, with a gradual decline in impairment as the glare source moves toward the side of the pilot. However, there was no significant interaction between glare duration and of glare angle.

17. Key Words Human Factors, Aircraft Simulation, Solar Panel Glare, Airport, Pilot Hazard		18. Distribution Statement Document is available to the public through the Internet: www.faa.gov/go/oamtechreports	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 15	22. Price

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

ACKNOWLEDGMENTS

Contents

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EVALUATION OF GLARE AS A HAZARD FOR
GENERAL AVIATION PILOTS ON FINAL APPROACH

INTRODUCTION

Solar power is a growing source of energy for airports and for their communities. For example, in 2012 Manchester-Boston International Airport completed installation of 42,000 photovoltaic panels (Manchester-Boston Regional Airport, 2012). In 2011, private development of a 75-acre solar farm on land owned by the Indianapolis International Airport began with an expected capacity to generate 15 gigawatts of electricity. The airport was collecting approximately $315,000 a year in rent for the land on which the solar farm was built (Indianaplois Airport Authority, 2011; Swiatek, 2013). The Denver International Airport currently has three separate solar arrays, and in June 2014, announced that a fourth solar installation will be built and altogether spread over 55 acres (Montgomery, 2012). In the same month, General Mitchell International Airport in Milwaukee, WI, completed acceptance of requests for proposals (RFP) to "evaluate the feasibility of siting a large-scale solar photovoltaic system at General Mitchell International Airport" (U.S. Department of Transportation, 2014). It is worth noting that there is no clear indication in the RFP as to how large this solar installation will be, but if some of the installations at other airports are an indication, it is likely to cover many acres in solar panels.

While solar power panels provide a useful means to generate revenue and to provide energy locally, they do pose a potential hazard to pilots, in the form of glare. For example at the Manchester-Boston Regional Airport, air traffic controllers (ATCs) reported significant problems seeing due to glare reflecting from the solar panels toward the tower. Aside from the Manchester-Boston Regional ATCs suffering from solar glare, reports from pilots flying near the Ivanpah Solar Electric Generating System have included complaints about the glare from the facility (Motley, 2014). Pilots have described the glare as "blinding," and at least one individual reported in the Aviation Safety Reporting System (ASRS) database that the glare was "like looking into the sun" and that they thought the glare was a hazard because they could not see if there was air traffic nearby (ASRS Database, 2013).

The effect of transient glare from a solar panel can produce a sudden increase, or flash of light. Sudden changes in the appearance or the presentation of new stimuli at a point within the visual field are known to capture attention (Yantis, 1993a; Yantis & Hillstrom, 1994), including interrupting attention allocated to another task (Yantis, 1993b). A particularly salient cue for the capture of visual attention is a sudden change in brightness within a point of the visual field (Theeuwes, 1991; Wright & Richard, 2003). The pulling of attention away from a primary task (such as flying) produces some level of distraction and introduces a secondary task (noting a source of glare) (Lavie,

2005; Wickens, Sandry, & Vidulich, 1983). Visual distractors, both internal and external to a vehicle, have been known to influence control (Engstrom, Johansson, & Östlund, 2005; Ranney, Garrott, & Goodman, 2000). Flooding the cockpit of an aircraft with glare will likely decrease visibility for the pilot thereby making it more difficult to control the aircraft. The increased difficulty will likely be reflected by increased cognitive load as the pilot will now have to work a bit harder to maintain visual contact with the runway, instruments, and the management of their aircraft.

In the current study, pilots were exposed to glare during a series of flights in a flight simulator, and their perceived impairment was recorded. During the approach phase of each flight, we simulated glare from one of four possible angles (0, 25, 50, and 90 degrees left of straight ahead), and for glare durations of either 0 (no glare control), 1, and 5 s. The glare was simulated using halogen lamps that, under the lighting conditions of our lab, approximated the visual effect of solar glare. During the flight, the pilots wore an EEG cap to record any changes in neural activity that would indicate increased cognitive and visual load as a function of glare exposure. An eye tracker was used to monitor eye movements to ascertain if they looked toward the glare and what compensatory eye movements were made in response to glare exposure. The results of the EEG and eye tracking will be reported in separate reports. Finally, we asked pilots to provide subjective ratings of their own perceptions of how the glare affected their ability to fly and to read their instruments. Additionally, we asked them to rate the similarity of the simulated glare to glare they have experienced in the real world.

METHODS

This study was completed using the AGARS Simulator (described in detail later) at the Federal Aviation Administration's Aerospace Human Factors Research Lab (AHFRL) at the Civil Aerospace Medical Institute (CAMI), which is located at the FAA Mike Monroney Aeronautical Center (MMAC) in Oklahoma City, OK.

Participants
All participants in this experiment were federal employees recruited via distribution of emails internal to the MMAC facility. The experiment was completed as part of the each employee's work activities, which required that the participants negotiate the time with their individual managers. Because this study was completed as part of the employee's normal work activities, no additional compensation was given. The minimum requirements for this study included having been a certified private pilot (though not necessarily current) and normal or corrected-to-normal visual acuity. A total of 20 participants coordinated

their time for participation. One was excluded from analysis due to early termination of his experiment session, leaving 19 participants, all male. All participants were required to provide their informed consent via two consent forms, one for CAMI and one for Sandia National Laboratories, approved by each institutions' Institutional Review Board.

Design

We combined four angles of glare exposure (0, 25, 50, and 90 deg) and two levels of exposure duration (1 and 5 s) to create eight possible experimental conditions. The durations were selected as they represent a range of transit times across solar installations at a variety of speeds. Additionally we had the pilots fly a single trial in which no glare was present as a control condition, thereby producing a total of nine conditions. Each pilot flew one trial of each of the nine conditions. The order of trials was randomized for each participant, so the pilot did not know if a glare event would occur during any given trial, or from what angle.

Stimuli and Apparatus

Glare Experience Questionnaire

The glare experience questionnaire asked questions about the pilot's experience with solar glare while flying, as well as some general demographic questions.

Pilot Demographics

The pilots were asked to indicate their current age, gender, how long they have been flying, if they wear corrective lenses (and if so what kind), and if they have had vision corrective surgery (and if so to indicate how long ago).

Questions Related to Solar Glare

Pilots were asked to provide ratings of their experience related to direct sunlight, glare from solar panels, and glare from other objects. For each, they were asked to indicate what stage of flight they had their encounter (departure, take-off, cruising, approach, touch-down), impairment of ability to fly the plane and the impairment to the ability to read their instruments (each on a 5-point scale: no impairment, slight impairment, moderate impairment, significant impairment, severe impairment), typical duration of exposure (less than 1 s, 1-5 s, 5-10 s, greater than 10 s), and to indicate what compensatory strategies they have used (use sun shade, use sunglasses, avert eyes, other). With regard to glare from other objects, we asked them to indicate the source of the glare.

AGARS Flight Simulator

The flight simulator used in this study was the Advanced General Aviation Research Simulator (AGARS). The AGARS is a simulation of a Piper PA-46 Malibu single-engine aircraft. Unique features of this simulator include the replacement of the hardware-based instrumentation with a touchscreen representation of flight instruments. This was done to mediate configurability of the cockpit for use across multiple research projects. For this study, we maintained use of the traditional round dial configuration.

AGARS Flight Simulator Host System

The AGARS simulation host computer is a custom-built system that uses a AMD Opteron 2218 processor with 1Gb of RAM. The operating system is Fedora Linux 12 and the simulation software was written by ZedaSoft, Inc.

AGARS Out-the-Window Display System

The AGARS out-the-window (OTW) display system used five Sharp Aqous 60-inch LC-60LE835U flat panel televisions mounted on stands in front and to the sides of the cockpit, thereby creating a segmented display system spanning 180 degrees and creating a reasonably realistic OTW scene.

Each of the OTW displays is driven by a custom-built computer. These computers have Intel, Inc. i7 CPUs, 12Gb DDR3 RAM, and two Sli-connected NVidia GTX 470 video cards with 128 Mb of memory. The computers are running the 64-bit edition of Microsoft Windows 7 Professional. The image generator (IG) software, which is responsible for the OTW scene, is VRSG 5.7.2 from MetaVR, Inc.

Navigation Map Display

A JeppView FlightDeck 3.5.6 GPS navigation map display was positioned above the glare shield and centered in the cockpit near the forward windscreen. The JeppView software was running on a Dell Optiplex 780 computer with an Intel Core 2 Duo 2.93 Ghz processor with 4 Gb RAM. The operating system of this computer was the 32-bit edition Windows 7 Professional. The display was a Faytech 9.5 inch touchscreen (model: FT10TMB).

Glare Simulation Devices

To simulate glare being reflected from solar panels, we used a series of four SoLux halogen bulbs (12 V, 50 W, MR16, black back) with a 10-d beam spread and a color temperature of 4700 K to reproduce the full solar spectrum. Each of the lamps was mounted atop a Leica Tri 100 tripod. Each light was controlled by its own control box, built by Sandia National Laboratories. Each control box featured a trigger switch, which, when thrown, activated a PTC-1A digital timer manufactured by Omega Engineering, Inc., which determined how long the attached lamp would stay on (1 or 5 s). The lamps, tripods, and control boxes are collectively referred to as the glare simulation devices (GSDs).

The four GSDs were placed straight ahead of the pilot (0 degrees), and at 25, 50, and 90 deg away from straight ahead on the left side of the simulator cockpit, between the cockpit and the simulator OTW view. The distance between the lamp and the pilot's eyes was approximately 0.8 m. Depending on the location of the lamp, the measured luminance at the eye was between ~1,000 – 2,000 Lux (measured using a digital Lux meter LX1330B), which corresponds to a corneal irradiance of ~10 – 20 W/cm² (1 W yields approximately 100 lumens of visible light in the solar spectrum). The subtended angle of the glare based on the bulb aperture of ~0.05 m and a distance of ~0.8 m was approximately 0.06 rad. The retinal irradiance was calculated from the measured corneal irradiance, subtended glare angle, and measured pupil diameter (~5 mm) to be ~0.024 – 0.048 W/cm². Together with the subtended glare angle of 0.06 rad (60 mrad), the retinal irradiance was sufficient to cause a temporary after-image, similar to solar glare reflected from flat solar panels (Ho, Ghanbari, & Diver, 2011; Ho, 2013).

Figure 1. Placement of two of the Glare Simulation Devices are at 5 deg and 50 deg.

Figure 2. Interior view of the AGARS cockpit, with the 0-deg GLD triggered.

Following trials with simulated glare, we asked pilots to rate their experience. The three questions and possible responses (on a 5-point rating scale) were as follows:

1. Rate the degree of impairment from the simulated glare on your ability to fly the plane.
   ☐ 1 = No impairment: Can easily perform functions necessary to fly the plane with no noticeable impact of glare
   ☐ 2 = Slight to no impairment: Can still perform functions necessary to fly the plane, but glare is noticeable
   ☐ 3 = Moderate impairment: Can perform functions necessary to fly the plane, but glare required some action (e.g., physically blocking glare, averting eyes)
   ☐ 4 = Significant impairment: Difficulty performing functions necessary to fly the plane, even after performing actions in response to glare
   ☐ 5 = Severe impairment: Unable to perform functions necessary to fly the plane
2. Rate the degree of impairment from the simulated glare on your ability to read your instruments.
   ☐ 1 = No impairment: Can easily read instruments and values (e.g., altitude, speed) with no noticeable impact of glare
   ☐ 2 = Slight to no impairment: Can still read instruments and values, but glare is noticeable
   ☐ 3 = Moderate impairment: Can read instruments and values, but glare required shifting of eyes, blinking, or refocusing in order to read values
   ☐ 4 = Significant impairment: Difficulty reading instruments and values, even after shifting of eyes, blinking, or refocusing
   ☐ 5 = Severe impairment: Unable to read instruments and values
   ☐ N/A (did not view instruments during or after glare event)
3. How similar was the simulated glare to actual glare you have observed while flying, if applicable?
   ☐ 1 = No similarity
   ☐ 2 = Slight similarity
   ☐ 3 = Moderate similarity
   ☐ 4 = Very similar
   ☐ 5 = Extremely similar
   ☐ Not applicable

For all trials, we asked the subjects the open-ended question "[are there] any additional comments or questions regarding this test or your experience that you would like to provide?"

Procedure

Pilot Preparation

Pilots were required to provide their informed consent prior to participation. Upon consent, we measured the pilot's head size in order to select the appropriate EEG cap. We then asked the pilot to enter the cockpit so that initial eye tracking camera calibration and seat position adjustments could be made. The pilots completed the glare experience questionnaire. The EEG cap was placed upon the pilot's head and the position and chin strap adjusted to ensure proper fit and comfort. Once all EEG electrodes indicated good signal, the pilot was reminded not to make any sudden head movements and then was escorted to and seated in the AGARS cockpit. We asked the pilot to verify the correct alignment of the GSDs, and made any minor adjustments that were required to optimize the glare simulation. Final eye tracking calibration was then performed.

Familiarization Flight

Each pilot was informed about the performance characteristics of the Piper Malibu simulated by the AGARS and was given a few minutes to become familar with the location and characteristics of the instrumentation. Once the pilot felt ready, we began one to three familiarization flights, depending on how quickly they became comfortable flying the AGARS. While familiarization took place, one of the researchers familiar with flying the AGARS remained available to the pilot to answer any questions and to guide them along the experimental route .

Flight Route

For all flights, the pilots flew from Max Westheimer Airport (KOUN) in Norman, OK, to the GALLY navigation fix, located in Newcastle, OK, at an altitude of 2,500 feet MSL (see Figure 3). From there, they headed north to Will Rogers International Airport (KOKC) to land on runway 35R. The pilots were able to use the GPS navigation display to maintain spatial awareness of their current location in relation to the GALLY navigation fix and KOKC 35R. Each flight lasted about 5 min.

Figure 3. *Map of flight route depicting the route flown by pilots in our study. Take off was from KOUN. Pilots then flew to the GALLY waypoint (Stacks on sectional charts) and then turned north to KOKC.*

The radios for AGARS were set to the frequencies for KOKC 35R automatically. This enabled localizer, glideslope, and distance measuring equipment (DME) instrumentation to work appropriately without intervention from the pilot. This was done to minimize their workload, particularly because the AGARS touchscreens can make manipulation of the radio dials extremely difficult, which would dramatically increase pilot workload.

We controlled glare with the GSDs. When a trial called for using glare, the appropriate GSD was selected and the exposure duration was programmed into the digital timer for that GSD. One of the researchers observed a display that replicated the DME display from the AGARS cockpit. The trigger for the GSD was activated when the DME was 2.6, which places the aircraft at 1 mile from the runway threshold, on final approach to landing at Will Rogers.

RESULTS

Glare Experience Questionnaire
Pilot Demographics
Pilots' mean age was 47.6 years (*SEM = 1.88*). The mean flight years was 21.7 (*SEM = 2.32*). Two pilots had stopped flying several years prior to participating in this experiment (one had ceased five years ago, while the other had not flown in 20 years). Both of these pilots demonstrated that their flying skills were sufficient for participation. Eleven pilots (58%) wore corrective lenses while flying. Of those who wore corrective lenses, nine (81%) wore glasses, one wore contacts, and one declined to respond. Three pilots had received vision corrective surgery, with a mean of 3.25 years since their surgery (SEM = 1.01).

As can be seen in Figure 4, the majority of participants had some real world experience with direct sunlight or with solar glare reflecting from other objects. From the Figure, it is also clear that the majority of encounters with sunlight and glare from other objects took place while the pilot was in cruise or on approach. Less than a third of pilots had encountered direct sunlight during departure or take-off. These results suggest that this study design is well-positioned to generalize outside the lab, since the experimental design exposed pilots to glare during approach, rather than another stage of flight such as take off. Of key interest was the low number of respondents (two) who had encountered glare from solar installations. This was likely due the lack of solar installations in the Oklahoma City area, where our subjects were recruited and may have spent the majority of their time flying.
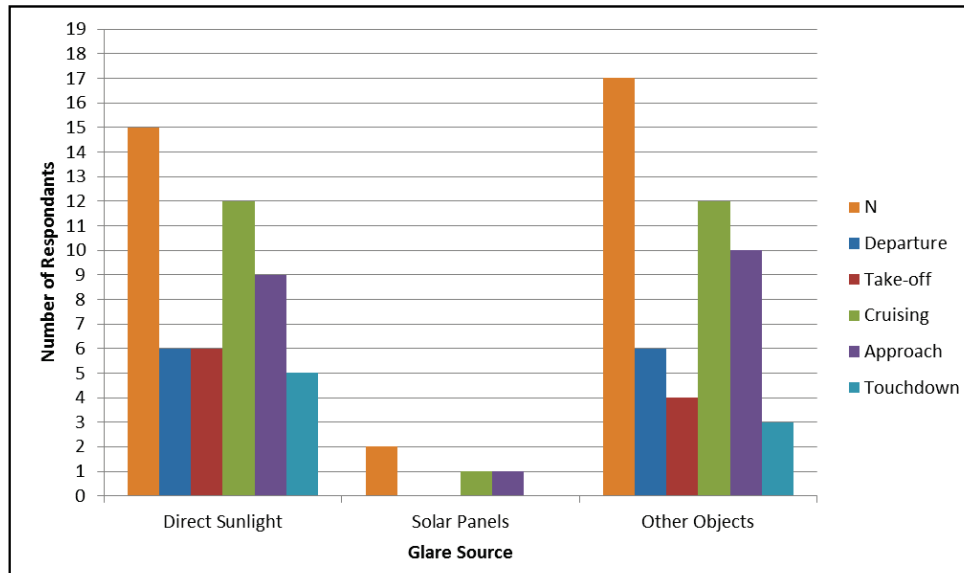

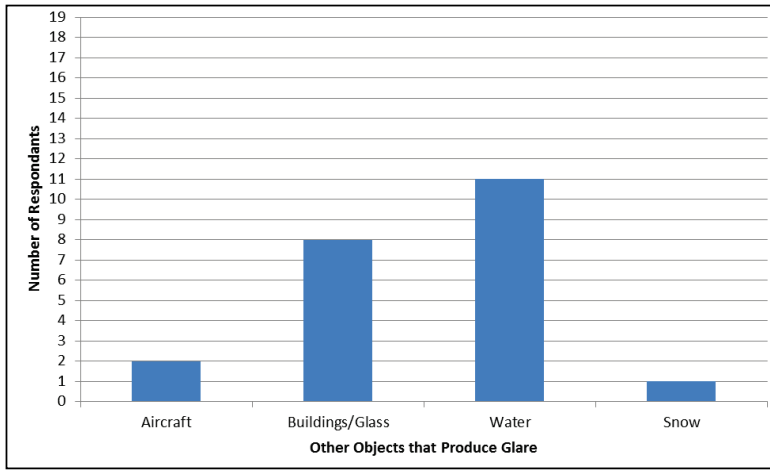*Figure 4.* Real-world sources of solar glare that pilots have encountered.

Figure 5. *Duration of glare from real-world objects encountered by pilots.*
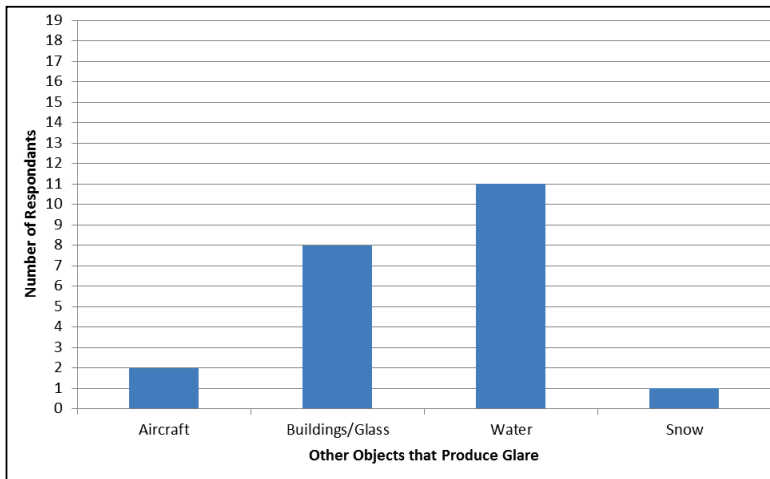

Figure 6. *Frequency of glare from sources other than direct sunlight or solar panels.*

Figure 5 shows that the majority of our pilots had encountered glare with durations between 1 and 10 s with longer durations being encountered for objects other than direct sunlight or solar panels. Figure 6 shows that, for most, glare emanated primarily from bodies of water.

AGARS Flight Simulator Data

The lateral deviation from the runway centerline of the initial touch down point was submitted to an analysis of variance (ANOVA) for within-subjects designs (a.k.a. repeated measures). In this instance, there were two factors (Independent Variables, or IVs): 1) duration with two levels (1 s and 5 s) and 2) angle of the simulated glare exposure (0, 25, 50, and 90 deg to the left of straight ahead). The outcome measure, or Dependent Variable (DV), was the lateral deviation of the initial touch-down point from centerline.

Neither duration, $F(1,18) = .406$, MSe = 5.282, $p < .532$, $\acute{\eta}^2 = .022$, nor the angle of simulated glare exposure was significant, $F(3,54) = 1.407$, MSe = 3.228, $p < .251$, $\acute{\eta}^2 = .073$. Likewise, no significant interaction was found between these two variables, $F(3,54) = .451$, MSe = 4.046, $p < .717$, $\acute{\eta}^2 = .024$.

It should be noted, however, that there were two runway impacts (crashes) during the course of the experiment. The first took place during a control condition during which no glare was present. This pilot, we suspect, may have been testing the limits of the simulator, because the pilot appeared to be showing signs of boredom, such as making delayed approaches requiring a steeper approach angle. Following this impact, the pilot appeared to fly much more conservatively. Since this pilot had no difficulty with any other landing, it seems more than coincidental that the one time he had a problem was also the one time he did not have a glare event during the main trials.

The second runway impact took place when the glare was presented straight ahead of the pilot for a duration of 5 s. This pilot bounced the aircraft twice while landing. The third contact was ultimately registered as an impact (crash). While the previously mentioned lack of significant groupwise interaction between glare angle and glare duration does not directly support *causation* of this particular impact, that notion is suggestive for this one case.

Post-Trial Questionnaire

Pilot ratings of perceived impairment of glare on the ability to fly the airplane and to read their instruments, for both the 1-s and the 5-s durations, are presented in Figures 5 and 6.
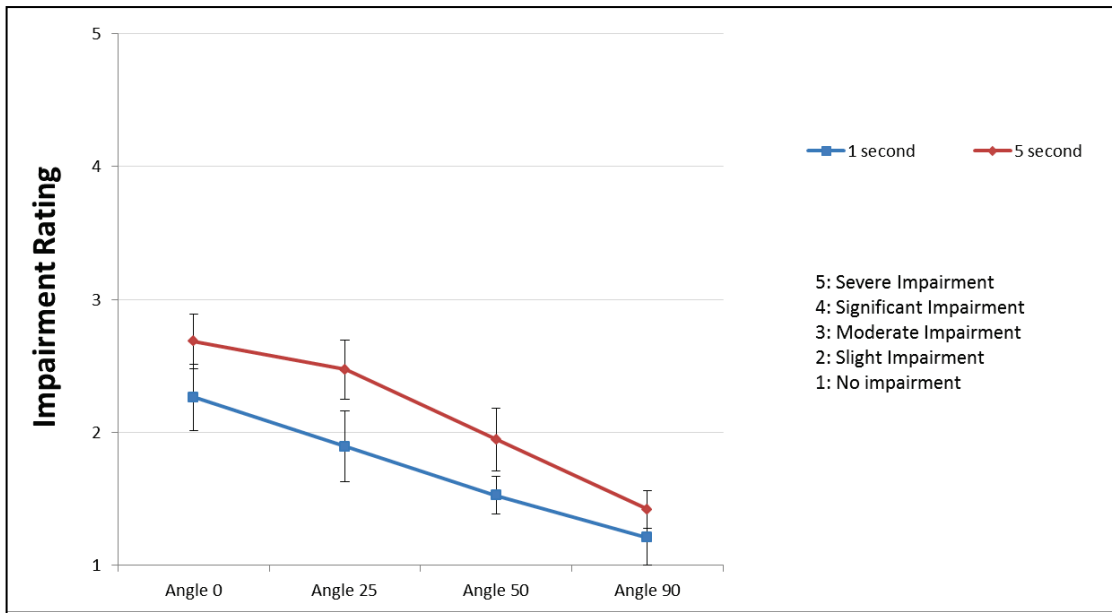
6

Figure 7. *Mean ratings of impairment to ability to fly based upon the angle and duration of simulated glare exposure. Error bars represent the standard error of the mean.*
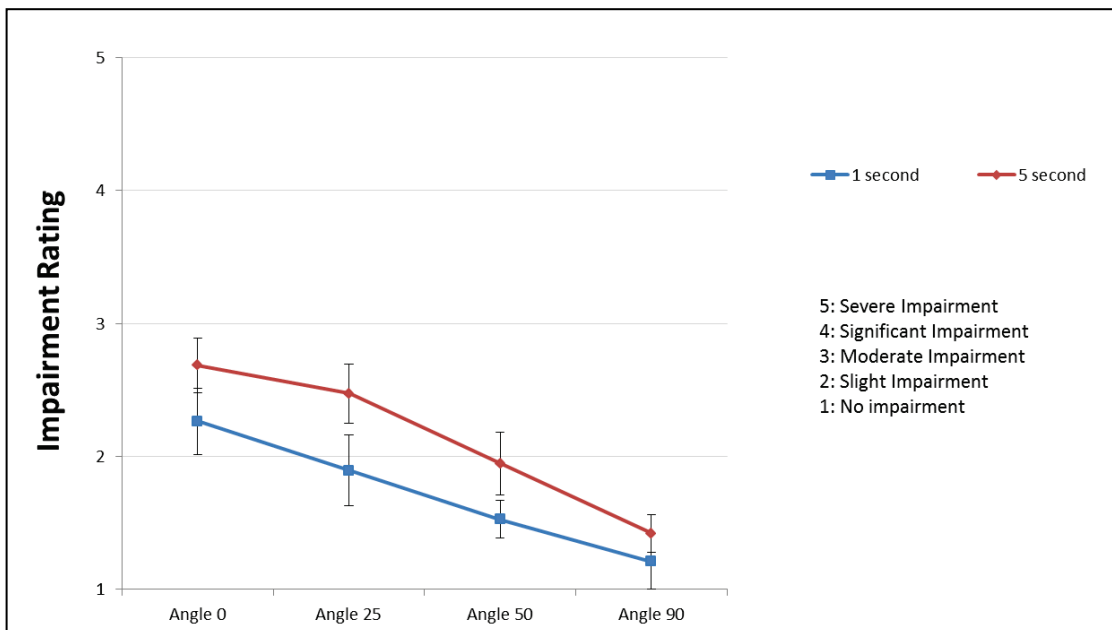

Figure 8. *Mean ratings of impairment to read instrumentation based upon the angle and duration of simulated glare exposure. Error bars represent the standard error of the mean.*

The average results for the 1- and 5-s durations are presented in Figure 7. It is obvious by looking at the Figures 7 and 8 that impairment is worse for glare sources that are straight ahead of the pilot, with a gradual decline in impairment as the glare source moves toward the side of the pilot. If we look at the ratings of impairment on the ability to fly, we can see that the mean rating, for both 1 s (M = 3.16, SEM = 0.23) and 5 s (M = 3.53, SEM = 0.16) glare durations at 0 deg is above 3, a rating of moderate impairment. At an angle of 25 deg, the mean impairment rating for an exposure duration of 5 s (M = 2.89, SEM = 0.20) is just below the rating of 3, and the error bar rises above the rating of 3. This indicates that this particular condition results in moderate impairment of the ability to fly. Also, at the angle of 25 deg,

the mean impairment rating for a glare duration of 1 s is M = 2.47, SEM = 0.25, indicating slight to moderate impairment.

For the control (no glare) condition, all pilots rated the impairment for both the ability to fly and impairment for reading their instruments as a 1 (no impairment). This indicated that they were able to fly the aircraft and see their instruments with no difficulty when glare was not present in a flight. However, since the absence of glare uniformly produced a rating of 1 (a clear floor effect) we excluded those data from further analysis because leaving them in would have automatically led to higher statistical significance when glare was present. We instead opted to leave those data out and focus solely on conditions in which glare was present to determine how those conditions differed from each other.

To isolate the sources of variation in our study, a doubly multivariate analysis was conducted. The doubly multivariate analysis is an extension of ANOVA for within-subjects designs that allows for the measurement of changes in multiple DVs as a function of different IVs. This analysis measured three DVs: the pilot rating of a) impairment of flying ability, b) impairment to read their instruments, and c) how similar the simulated glare was to what had been experienced in the real world. Two IVs were used in this analysis. The first was the duration of the glare exposure with two levels (1 s and 5 s). The second was the angle of glare exposure, with four levels (0, 25, 50, and 90 deg to the left from straight ahead). Wilks' λ was used in the multivariate testing. Wilks' λ, also called the maximum likelihood criterion, is a multivariate statistic that measures the proportion of variance in the DVs that is unaccounted for by the IV(s). Because it is measuring the variance that is unaccounted for, a small Wilks' λ is associated with a statistically significant result and therefore rejection of the null hypothesis.

There was a significant main effect of glare duration, Wilks' ή = .508, $F(9,10) = 9.325$, $p < .011$, $ή^2 = .492$. This indicates that there is a difference among the DVs based upon the duration of glare exposure. There was also a significant main effect of the angle of glare exposure, Wilks' ή = .106, $F(9,10) = 9.325$, $p < .001$, $ή^2 = .894$. This indicates that there was a difference among the DVs based upon the angle of glare exposure. However, there was not a significant interaction between duration of glare exposure and the angle of glare exposure, Wilks' ή = .711, $F(9,10) = .452$, $p < .877$, $ή^2 = .289$.

Given the significant multivariate tests, univariate tests were carried out to further parse the relation supported by the multivariate main effects. These univariate tests are two-factor ANOVAs for within-subjects designs. Each of these univariate tests measured the effect that the two IVs had on a single DV (the pilot's rating of impairment on flying ability, the pilot's rating of impairment to read the instruments, and the pilot's rating of how similar the simulated glare was to what they had experienced in the real world).

The first univariate test assessed how glare angle and duration affected pilots' rated impairment of glare on flying ability. This test showed a significant main effect of simulated glare duration on impairment of flying ratings, $F(1,18) = 11.272$, $MSe = .675$, $p < .004$, $ή^2 = .385$, with the 5-s duration having a higher overall mean (M = 2.645, SEM = .136) than the 1 s duration (M = 2.197, SEM = .128). There was also a significant main effect of the simulated glare exposure angle on the pilot ratings of how it affected their ability to fly, $F(1,18) = 32.898$, $MSe = .675$, $p < .000$, $ή^2 = .646$, with an orderly rating of straight ahead as the most impairing (M = 3.342, SEM = .171), 25 deg left of straight ahead as second most impairing (M = 2.684, SEM = .172), 50 deg left of straight ahead as less impairing (M = 2.026, SEM = .130), and 90 degr to left of straight ahead as the least impairing (M = 1.632, SEM = .166).

To determine if there were significant differences between the ratings of how piloting ability was affected for each of the various angles, pairwise comparisons were performed. A Bonferroni correction was used to control for familywise error rate inflation. The pairwise comparisons of angle of exposure revealed that straight ahead was rated as significantly higher than 25 deg to the left of straight ahead (p < .038). Likewise, straight ahead was found to be significantly higher than 50 deg to the left of center (p < .000), and 90 deg left of center (p < .000). Further, 25 deg left of center was found to result in a higher rating than 50 deg left of center (p < .001), and 90 deg left of center (p < .000). Finally, with regard to the rating impact to piloting ability, there was no significant difference found between 50 deg and 90 deg left of the center (p < .236).

The second univariate test we conducted assessed how glare angle and duration affected pilot ratings of their ability to read instruments. We found a significant main effect of glare duration on rated ability to read instrumentation, $F(1,18) = 11.046$, $MSe = .572$, $p < .004$, $ή^2 = .385$, with the 5-s duration having a higher overall mean (M = 2.132, SEM = .151) than the 1-s duration (M = 1.724, SEM = .154).

Mauchly's test for Sphericity determines whether the variances across the different conditions are equal. When the variances across levels are equal, the sphericity assumption of an ANOVA has been met and Mauchy's test for Sphericity will not be significant. When Mauchly's test for Sphericity is significant, it means that the sphericity assumption has been violated, which results in a greater risk of a Type II error (failure to reject the null hypothesis). To compensate for this, the degrees of freedom for the ANOVA have to be adjusted; typically by using a Greenhouse-Geisser correction. When analyzed for the effect of glare angle on pilot ratings of their ability to read their instruments, we found that Mauchly's test for Sphericity was significant, $ή^2(5) = 12.362$, $p < 0.030$. The corrected ANOVA showed a significant main effect of simulated glare exposure angle on ratings of how it affected their ability to read the instruments, $F(2.281, 46.319) = 13.611$, $MSe = .948$, $p < .000$, $ή^2 = .646$, with an orderly rating of straight ahead as the most impairing (M = 2.474, SEM = .189), 25 deg left of straight ahead as second most impairing (M = 2.184, SEM = .214), 50 deg left of straight ahead as less impairing (M = 1.737, SEM = .168), and 90 deg to left of straight ahead as the least impairing (M = 1.316, SEM = .159).

To determine if there were significant differences between the ratings of how the ability to read instrumentation was impacted for each the various angles of simulated glare, pairwise comparisons were performed using a Bonferroni correction. The pairwise comparisons of angle of exposure revealed that straight ahead is not rated as significantly higher than 25 deg to the left of straight ahead (p < 1.000). However, straight ahead was found to be significantly higher than 50 deg to the left of center (p < .014) and 90 deg left of center (p < .000). Further, 25 deg left of center was significantly higher than 50 deg left of center (p < .014) and 90 deg left of center (p < .006). Finally, with regard to the rating impact to the ability to read instrumentation, it was found that there was not a significant difference between 50 deg and 90 deg left of the center (p < .098).

The last univariate test assessed how glare angle and duration affected pilot ratings of the simulated glare verse glare they had

experienced while flying in the real world. We found no main effect of duration on ratings of the similarity of represented glare to real-world glare ($F(1,18)$ = .471, MSe = .893, $p < .501$, $\acute{\eta}^2$ = .026). We analyzed the effect of the angle of glare exposure on pilot's ratings of the similarity of the simulated glare to real-world glare, Mauchly's test was again significant($\acute{\eta}^2(5)$ = 11.218, $p < 0.048$). Subsequent Greenhouse-Geisser-corrected ANOVA was not significant ($F(2.117,38.102)$ = .626, MSe = 1.370, $p < .549$, $\acute{\eta}^2$ = .034). This means that regardless of the duration or the angle of the glare, the ratings of how realistic they perceived the simulated glare to be remained about the same.

DISCUSSION

AGARS Flight Simulator Data

Results of the landing data showed no significant, systematic lateral deviation from runway centerline, regardless of the duration or angle of simulated glare presented to the participant.

The one case that we considered to be of any potential concern was when a pilot crashed during landing with the glare presented straight ahead for a duration of 5 s. However, we would suggest tempering any concern by pointing out that if there was a problem with that particular angle and duration, we would have likely seen more individuals who had crashed.

Post-Trial Questionnaire

Data from the post-trial questionnaire demonstrate that, for the most part, higher glare durations result in greater self-perceived impairment in the pilots' ability to safely fly an aircraft and to read aircraft instrumentation relative to shorter durations. Further, as expected, the more forward-facing the glare was, the more impairment the pilots reported experiencing. More precisely, we found that when glare was present, the ability to read aircraft instrumentation was not statistically different between glare that was presented straight ahead and when it was 25 deg

to the left of straight ahead. Likewise, no statistical difference was found between 50 deg and 90 deg of straight ahead. Taken together, this suggests that as far as reading instrumentation is concerned, two groupings of angles resulted in similar impairment among the member angles: The first grouping included the member angles of 0 and 25, and the second grouping included the member angles of 50 and 90. While there was a significant increase in these ratings, it is still considered to be less than a moderate impairment on the ability to read instrumentation. Though the rating was, ultimately, below our threshold of "moderate impairment," one could speculate that longer durations may result in higher impairment ratings for reading instrumentation, particularly for angles of 0 and 25 deg of straight ahead.

In terms of how glare impacted the ability to fly, we found a similar effect of glare duration as described above: A longer duration resulted in greater self-reported impairment to the ability to land on a runway center. We found that glare from the angles of 50 and 90 deg was not statistically different from each other with regard to the relative impairment to the ability to fly. Interestingly, there is a statistically significant increase in the ratings of impairment when glare comes from an angle of 25 deg, and a still larger increase in the ratings of impairment for glare that is straight ahead. Again, the closer the glare was to straight ahead, the more likely it became problematic for the pilot, and glare toward the side is unlikely to be a problem.

Figure 9 shows that ratings of the impairment to the ability to fly for glare from straight ahead were above a rating of 3. Additionally glare from 25 deg for a 5 s duration yielded a rating that was, statistically, indistinguishable from a rating of 3. Therefore, it is reasonable to say that glare from straight ahead or from 25 deg (if it is long enough) will result in moderate impairment.

To summarize, the safe course of action would appear to be to locate sources of glare such that they do not produce glare from angles less than 50 deg from the pilots' view straight ahead on approach to landing.
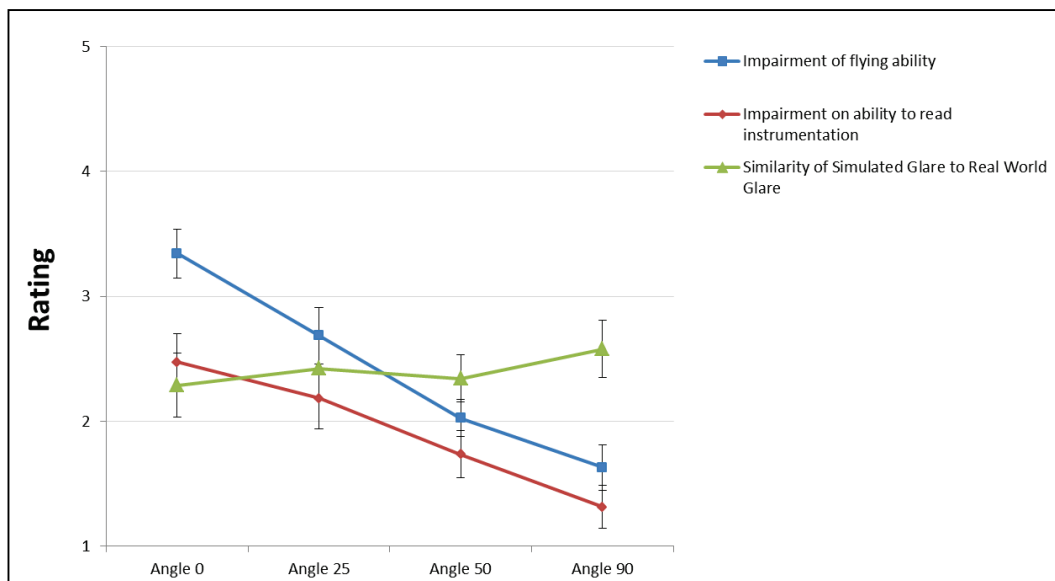

Figure 9. Mean ratings of impaired flying ability, impaired ability to read instrumentation, and the similarity of simulated glare to real glare, as a function of glare exposure angle. Error bars represent one standard error of the mean.

CONCLUSIONS

The presence of glare was associated with the most impairment in the pilot's ability to see their instruments and to fly their airplane when the glare was straight ahead, as well as slightly to the side. The more forward the glare is and the longer the glare duration, the greater the impairment to the pilots' ability to see their instruments and to fly the aircraft. These results taken together suggest that any sources of glare at an airport may be potentially mitigated if the angle of the glare is greater than 25 deg from the direction that the pilot is looking in. We therefore recommend that the design of any solar installation at an airport consider the approach of pilots and ensure that any solar installation that is developed is placed such that they will not have to face glare that is straight ahead of them or within 25 deg of straight ahead during final approach.

REFERENCES

ASRS Database. (2013, 08). ACN: 1109473.

U.S. Department of Transportation. (2014, June). RFP-General Mitchell International Airport solar energy feasibility assessment. Retrieved from: http://county.milwaukee.gov/ImageLibrary/Groups/cntyArchEng/dturzai/09172013forward/GMIASolarEnergyRFP5-14.pdf

Engstrom, J., Johansson, E., & Östlund, J. (2005). Effects of visual and cognitive load in real and simulated motorway driving. *Transportation Research Part F, 8*, 97–120.

Ho, C.K., Relieving a Glaring Problem (2013, April). *Solar Today Magazine*, American Solar Energy Society: Boulder, CO. p. 28 - 31. Retrieved from: http://www.omagdigital.com/publication/?i=152579&p=28

Ho, C.K., C.M. Ghanbari, and R.B. Diver (2011). Methodology to assess potential glint and glare hazards from concentrating solar power plants: Analytical models and experimental validation, *Journal of Solar Energy Engineering*, 133(3), pp. 031021-1 - 031022-9.

Indianaplois Airport Authority. (2011, September 20). *Construction to begin on Indianapolis International Airport Solar Farm*. Indianapolis, IA. Published by Indianapolis Airport Authority. Retrieved from http://www.indianapolisairport.com/admin/uploads/614/9.20.11%20solar%20farm%20development.pdf

Lavie, N. (2005). Distracted and confused? Selective attention under load. *Trends on Cognitive Sciences, 9*(2), 75-82.

Manchester-Boston Regional Airport. (2012). *Solar project*. Manchester, NH, USA. Published by the Manchester-Boston Regional Airport. Retrieved from http://www.flymanchester.com/newsletters/holiday-2012/solar-project

Montgomery, H. (2012, June 18). Fourth Solar Array Opens at Denver International Airport. Denver, CO, USA. Retrieved from http://business.flydenver.com/pr/DIAPR_140618_8g.pdf

Motley, T. R. (2014). *Pilot complaints of visual impacts from Ivanpah solar electric generating system*. Las Vegas, NV. Docketed by the California Energy Commission, Docket No. 09-AFC-07C, TN#202694. Retrieved from: http://docketpublic.energy.ca.gov/PublicDocuments/09-AFC-07C/TN202694_20140714T114742_Letter_Re_Pilot_Complaints_of_Visual_Impacts_from_Ivanpah_Solar.pdf

Ranney, T. A., Garrott, W. R., & Goodman, M. J. (2000). *NHTSA driver distraction research: Past, present, and future*. Washington, DC: NHTSA. Paper No. 233. Retrieved from: http://www-nrd.nhtsa.dot.gov/pdf/esv/esv17/proceed/00177.pdf

Swiatek, J. (2013, October 19). Indianapolis airport solar farm is largest of its kind. *The Indianapolis Star*. Indianpolis, Indiana, USA. Retrieved from http://www.indystar.com/story/money/2013/10/18/solar-farm-at-indianapolis-international-airport-is-soaking-up-the-sun/3008427/

Theeuwes, J. (1991). Exogenous and endogenous control of attention: The effect of visual onsets and offsets. *Perception & Psychophysics, 49*(1), 83-90.

Wickens, C. D., Sandry, D. L., & Vidulich, M. (1983). Compatibility and resource competition between modalities of input central processing, and output. *Human Factors, 25*(2), 227-248.

Wright, R. D., & Richard, C. M. (2003). Sensory mediation of stimulus-driven attentional capture in multiple-cue displays. *Perception & Psychophysics, 65*(6), 925-938.

Yantis, S. (1993a). Stimulus-driven attentional capture. *Current Directions in Psychological Science, 2*(5), 156-161.

Yantis, S. (1993b). Stimulus-driven attentional capture and attentional control settings. *Journal of Experimental Psychology: Human Perception and Performance, 19*(3), 676-681.

Yantis, S., & Hillstrom, A. P. (1994). Stimulus-driven attentional capture: Evidence from equiluminant visual objects. *The Journal of Experimental Psychology: Human Perception and Performance, 20*(1), 95-107.