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Federal Aviation Administration
William J. Hughes Technical Center
Atlantic City International Airport, NJ 08405

# The Effect of Weather State-Change Notifications on General Aviation Pilots' Behavior, Cognitive Engagement, and Weather Situation Awareness

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**16. Abstract**
**Objective**: Results from the WTIC Phase 2 study showed that general aviation (GA) pilots performed poorly at detecting aviation routine weather report (METAR) symbol changes during flight (Ahlstrom & Suss, 2014)—attributed to the change-blindness phenomena. Here, we address this gap by examining the potential benefits of weather state-change notifications on pilots' behavior and Weather Situation Awareness (WSA) during a simulated flight. A second objective of this study was to assess pilot sensitivity to weather symbology changes on Topological, Visual Flight Rules (VFR), and Instrument Flight Rules (IFR) aeronautical map backgrounds in a change-detection experiment. **Method**: Seventy-three GA pilots volunteered to participate in the study. During a simulated weather scenario, participants were randomly assigned to an experimental or a control group and flew a single-engine GA aircraft, initially under Visual Meteorological Conditions (VMC). The experimental group was equipped with a vibrating bracelet that notified participants of state-changes to displayed METAR, Special-Use Airspace (SUA), and Significant Meteorological Information (SIGMET) symbols. During the simulation, we recorded each participant's horizontal and vertical flight profile, WSA, decision-making, cognitive engagement, weather presentation interaction, and distance from the aircraft to hazardous weather. Finally, we used a change-detection experiment to assess participant sensitivity to changes in weather symbols on three different backgrounds. **Results**: By assessing WSA, we found that the experimental group provided credibly more communications of weather information and maneuver/course change information and a higher number of "out-the-window" reports to the *pilot following* than the control group provided. This supports our hypothesis that weather state-change notifications result in earlier and more accurate recognition of weather state-changes and, thereby, positively improves participant WSA. The results of distance-to-weather analyses showed that both groups kept similar distances to 30 dBZ precipitation cells. It also showed, however, that participants in both groups flew closer to hazardous weather than what is recommended in current guidelines. Although not a credible difference, there were more participant reports of VFR flights into Instrument Meteorological Conditions (IMC) in the control group (N = 33) than in the experimental group (N = 27). When analyzing the functional near-infrared (fNIR) data, we found credibly higher prefrontal oxygenation levels in the control group compared to the experimental group. We attribute the reduced cognitive load in the experimental group to increased participant WSA. Because of the state-change notifications, participants were more attentive to information on the weather presentation, which enhanced planning and decision-making and reduced cognitive load. Finally, participant discrimination performance for symbol changes was low on the Topological, IFR, and VFR map backgrounds when compared to the performance of a simulated group of *ideal observers*. We interpret these findings to indicate that much work is still needed to optimize the symbology for cockpit weather presentations to achieve good symbol discrimination and reduce the time needed to differentiate weather presentation elements on all backgrounds. **Conclusion**: Weather state-change notifications improved WSA and reduced cognitive workload. However, these improvements did not translate to changes in participants' weather-avoiding behavior, indicating gaps in pilot understanding of the information or gaps in pilot decision making. **Applications**: This simulation is part of an ongoing assessment of the effects of weather-presentation symbology related to the optimization of weather presentations in cockpits.

**17. Key Words**
Change Detection
Cockpit Simulation
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Symbol State-Change Notification
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## Acknowledgments

This research was sponsored by the Federal Aviation Administration (FAA) Weather Technology in the Cockpit (WTIC) Program Office (ANG-C61). The study plan was reviewed and approved by the FAA Institutional Review Board (IRB). Interested readers can perform their own Bayesian analyses by downloading the free Bayesian software (including installation instructions: http://doingbayesiandataanalysis.blogspot.com/search/label/installation) used in this study.

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## Executive Summary

Results from the Weather Technology in the Cockpit (WTIC) Phase 2 study showed that General Aviation (GA) pilots performed poorly at detecting METAR symbol changes during flight (Ahlstrom & Suss, 2014)—attributed to the well-documented *change-blindness* phenomena (Rensink, 2002). Here, we address this gap by examining the potential benefits of weather state-change notifications (via tactile vibrations) on pilots' behavior and Weather Situation Awareness (WSA) during a simulated flight.

During this WTIC project, researchers used the Federal Aviation Administration (FAA) William J. Hughes Technical Center (WJHTC) Cockpit Simulator Facility to perform a cockpit simulation and a *change-detection* experiment to assess GA pilot decision-making and WSA. The cockpit simulation provided an objective measurement of pilot sensitivity to changing weather information during flight. The change-detection experiment focused on pilot sensitivity to element changes in weather presentations.

During a simulated weather scenario, 73 participants were randomly assigned to an experimental group or a control group and flew a single-engine GA aircraft, initially under Visual Meteorological Conditions (VMC).

During the flight, both groups had access to a weather presentation displayed on a 15" Liquid Crystal Display (LCD) monitor mounted in the center of the cockpit dashboard. The weather presentation was configured in a split mode with Electronic Flight Bag (EFB) information, such as airport configuration maps or approach plates, on the left side and weather information on the right side. The weather presentation was a plan view, with an aircraft position symbol, in a track-up configuration. The weather information layered the Flight Information Services-Broadcast (FIS-B) basic products with graphical and text-based information for Airmen's Meteorological Information (AIRMET), Significant Meteorological Information (SIGMET), Aviation Routine Weather Report (METAR), Next-Generation Radar (NEXRAD), Notice to Airmen (NOTAM), Pilot Report (PIREP), Special Use Airspace (SUA), Terminal Area Forecast (TAF), Wind/Temperature, and Lightning information.

The experimental group was equipped with a vibrating bracelet that notified participants of state-changes to displayed METAR, SUA, and SIGMET symbols. During the simulation, we recorded each participant's horizontal and vertical flight profile, WSA, decision-making, cognitive engagement (fNIR; oxygenation), weather presentation interaction, and distance from the aircraft to hazardous weather. Finally, we used a change-detection experiment to assess participant sensitivity to changes in weather symbols on three different backgrounds.

The following four hypotheses ($H_1$ - $H_4$) were proposed to better define the specific objectives of the study and to evaluate the outcome (see Table):

1. Implementing a tactile state-change notification function to the presentation of selected weather information will result in earlier and more accurate pilot recognition of the weather-state change associated with the notification function.
2. Earlier recognition of weather-state changes will afford pilots more time to take appropriate action to avoid adverse weather.

3. Earlier adverse weather avoidance decision-making will result in pilots maintaining a recommended distance from the weather event.
4. Implementing tactile weather notification functions without degrading pilot performance on safety-related flight tasks, actions, and decisions.

**Table. Summary of Study Hypotheses and Outcomes**

| Hypothesis | Supported by study results | Not supported by study results |
|---|---|---|
| $H_1$: Implementing a tactile state-change notification function to the presentation of selected weather information will result in earlier and more accurate pilot recognition of the weather-state change associated with the notification function. | √ | |
| $H_2$: Earlier recognition of weather-state changes will afford pilots more time to take appropriate action to avoid adverse weather. | | × |
| $H_3$: Earlier adverse weather avoidance decision-making will result in pilots maintaining a recommended distance from the weather event. | | × |
| $H_4$: Implementing tactile weather notification functions without degrading pilot performance on safety-related flight tasks, actions, and decisions. | √ | |

When assessing participant WSA, we found that the experimental group provided credibly more communications of weather information and maneuver/course change information and provided a higher number of "out-the-window" reports than the control group. This supports our $H_1$ hypothesis that implementing tactile weather notification functions result in earlier and more accurate recognition of weather state-changes and, thereby, positively improves participant WSA.

The results of distance-to-weather analyses showed that both groups kept similar distances to 30 dBZ precipitation cells. It also showed, however, that participants in both groups flew much more closely to hazardous weather than what is recommended in current FAA guidelines. This outcome does not support our $H_2$ and $H_3$ hypotheses.

Although not a credible difference from a statistical point of view, there were more participant reports of VFR flights into IMC conditions in the control group (N = 33) than in the experimental group (N = 27).

When analyzing the fNIR oxygenation data, we found credibly higher prefrontal oxygenation levels in the control group compared to the experimental group. We attribute the reduced cognitive load in the experimental group to increased participant WSA. Because of the state-change notifications, participants were more attentive to information on the weather presentation, which enhanced planning and decision-making and reduced the cognitive load. This outcome supports our $H_4$ hypothesis.

Participant discrimination performance for symbol changes was low on the Topological, IFR, and VFR map backgrounds when compared to the performance of a group of ideal observers. We interpret these findings to indicate that much work is still needed to optimize the symbology for cockpit weather presentations to achieve good symbol discrimination and reduce the time needed to differentiate weather presentation elements on all backgrounds.

We conclude that weather-change notifications improved WSA and reduced cognitive workload. However, these improvements did not translate to a change in participants' weather-avoiding behavior. These results provide valuable empirical data for proposed developments and enhancements to GA cockpit weather presentations as well as any addition of enhanced weather information to support Next Generation Air Transportation System (NextGen) concepts. However, the results also point to potential deficiencies in GA weather hazard and weather display training and point to enhanced ways to use weather information while in flight.

Therefore, for future research, we recommend an assessment of the effect of pilot training to improve user trust in weather presentations. We also recommend GA pilot training in both (a) how to correctly interpret weather information and (b) how to translate this information into improved flight decisions. Finally, we recommend that future research develops weather presentations with optimal luminance contrast between weather elements and the backgrounds.

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# 1. INTRODUCTION

This project was the third phase of a Weather Technology in the Cockpit (WTIC)-sponsored initiative to assess the operational importance of variations in GA pilot decision-making and behavior from the use of cockpit weather presentations.

During Fiscal Year 2011 the WTIC program funded and successfully completed Phase 1, which explored the effects of cockpit weather presentations on General Aviation (GA) pilot weather avoidance, weather presentation usage, and cognitive workload (Ahlstrom & Dworsky, 2012). Results originating from Phase 1 highlighted that variation in weather presentations (i.e., colors and symbols) affected participant behavior and decision-making. Notable participant group differences included different deviation paths around weather, variable visual scanning behavior, and changes in cognitive workload. However, Phase 1 was not intended to examine the potential operational impact (select safety and efficiency attributes) that could be attributed to variations in participant behavior. To address the issue of operational impacts from weather symbology variations the WTIC research team planned and conducted a Phase 2 study.

In the Phase 2 study a between-subjects change detection task was coupled with three weather presentations in a cockpit simulator Visual Flight Rules (VFR) flight designed to assess pilots' sensitivity to changes in aviation routine weather report (METAR) symbols during flight (Ahlstrom & Suss, 2014). Results from Phase 2 showed that participants performed poorly at detecting METAR symbol changes regardless of the weather presentation type—attributed to the change-blindness phenomena. Change blindness (Rensink, 2002) refers to the phenomenon where human observers fail to perceive changes in their field of view, like when new objects appear in an image or when objects change color and/or shape. This phenomenon is particularly strong during multitasking situations, such as those experienced during single pilot operations. Army researchers (Durlach, 2004) have also found evidence for operator change blindness, and suggested that symbol presentations need augmentation of intelligent alerts or notifications to improve operator change detection performance. The effect of symbol augmentation was investigated by O'Hare and Waite (2012), who found that pilots recalled more information from METARs when the information was presented with both text and symbols.

To address the gap found in the Phase 2 study—that is, participants performed poorly at detecting METAR symbol changes during flight—the WTIC research team planned and conducted a Phase 3 study. The objectives of the Phase 3 study were (a) to assess the effect on pilot weather change-detection behavior from the use of tactile state-change notifications and (b) to assess pilot sensitivity to symbol changes.

## 1.1 Purpose

The overarching goal of this study was to address the gap found in the Phase 2 study and to perform a human factors assessment of cockpit weather presentations on GA pilot behavior and decision-making. The main objectives of this study are

- to determine if the use of weather state-change notifications (via tactile feedback) improves pilot weather-change detection (simulation flight) by overcoming the change blindness effect seen in Phase 2.
- to evaluate pilot sensitivity to symbol changes in weather presentations with different backgrounds (*change-detection* experiment).

### 1.2 Simulation Hypotheses

The following four hypotheses were proposed to better define the two specific objectives of the goal of the study:

1. Implementing a tactile state-change notification function to the presentation of selected weather information will result in earlier and more accurate pilot recognition of the weather-state change associated with the notification function.
2. Earlier recognition of weather-state changes will afford pilots more time to take appropriate action to avoid adverse weather.
3. Earlier adverse weather avoidance decision-making will result in pilots maintaining a recommended distance from the weather event.
4. Implementing tactile weather notification functions without degrading pilot performance on safety-related flight tasks, actions, and decisions.

## 2. METHOD

During the simulation, we used a GA cockpit simulator with a 180° out-the-window-view. For the change-detection experiment, we used the same Stimulus Experiment System (SES) and change-detection paradigm used by Ahlstrom and Suss (2014).

### 2.1 Participants

Seventy-three GA pilots participated as volunteers during the study. Participants came from a pool of pilots with commercial, military, and private aviation backgrounds. We randomly allocated each participant to either an experimental group or a control group. Each participant performed a simulated flight and a change-detection experiment. Six participants did not fly in the simulator due to technical issues. Characteristics of the remaining participants are described in Table 1.

**Table 1. Descriptive Characteristics of Study Participants**

| | | | | Flight hours accrued | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Age (years) | | Total | | Instrument | | Instrument (last 6 months) | |
| Group | *n* | Mdn | Range | Mdn | Range | Mdn | Range | Mdn | Range |
| Exp | 33 | 58 | 21–77 | 9,000 | 75–23,000 | 1,000 | 0–10,000 | 2 | 0–200 |
| Control | 34 | 61.5 | 21–86 | 6,500 | 100–30,000 | 550 | 0–25,800 | 7 | 0–90 |

*Note.* Mdn = Median. The median is the numerical value separating the upper half of a data sample from the lower half.

### 2.1.1 Informed Consent Statement

Each participant read and signed an Informed Consent Statement (Appendix A) before starting the simulation flight. The informed consent statement describes the study, the foreseeable risks, and the rights and responsibilities of the participants, including a reminder that participation in the study is voluntary. It also stated that the participant could withdraw from participation at any time without penalty. All the information that the participant provided to us, including Personally Identifiable Information (PII), has protection from release except as required by statute. Signing the form indicated consent and that the participant understood his or her rights as a participant in the study.

### 2.1.2 Biographical Questionnaire

Participants completed a brief Biographical Questionnaire (see Appendix B). This questionnaire consisted primarily of questions related to pilots' flight experience and previous experience with weather displays.

### 2.1.3 Post-Scenario Questionnaire

All participants completed a 10-item rating-scale questionnaire (see Appendix C), including an additional yes or no item and an open-answer item to report any discomfort with the functional Near Infrared (fNIR) sensor.

## 2.2 Research Personnel

The research team (see Appendix D) used similar methods and simulation equipment for the present study as was used in the Ahlstrom and Dworsky (2012) and Ahlstrom and Suss (2014) studies. Members of the research team set up the simulations and experiments, developed and tested scenarios, prepared the SES for operation, conducted briefings, collected data, and wrote this final report.

## 2.3 Equipment

### 2.3.1 GA Cockpit Simulator

The simulation was performed in a GA cockpit simulator configured to simulate a Mooney Bravo single-engine aircraft (see Figure 1). The cockpit simulator is an integrated system that comprises a simulator-technician workstation, a cockpit system, and a voice communications system. The simulator was enclosed (fuselage) and equipped with a 180° out-the-window view. The weather presentation was displayed on a 15" Liquid Crystal Display (LCD) monitor mounted in the center of the dashboard. The cockpit simulator ran on the Windows 7 operating system, using Microsoft Flight Simulator 2004 via the Project Magenta workstation control scheme for a single-engine aircraft. The out-the-window view was generated by the Lockheed Martin Prepare 3D software with weather information provided by METAR strings.

*Figure 1*. The simulator cockpit.

### 2.3.2 Cockpit Glass Panel

The cockpit simulator used a glass cockpit panel template (see Figure 2). It was the same equipment used by Ahlstrom and Dworsky (2012) and Ahlstrom and Suss (2014).


*Figure 2*. The cockpit glass display.

### 2.3.3 Weather Presentation

During the simulation, participants used a weather presentation displayed on a 15" LCD monitor (see Figure 3) mounted in the center of the cockpit dashboard. The weather presentation was designed to have a simple menu structure to reduce the time needed for participant training. Therefore, this design is not found on commercially available weather presentations. However, we used commercially available weather symbology and background maps. The weather presentation was configured in a split mode with Electronic Flight Bag information (EFB), such as airport configuration maps or approach plates, on the left side and the weather information on the right side. The weather presentation was a plan view with an aircraft position symbol, in a track-up-configuration. The weather information layered the Flight Information Services-Broadcast (FIS-B) basic products with graphical and text-based information for Airmen's Meteorological Information (AIRMET), Significant Meteorological Information (SIGMET), Aviation Routine Weather Report (METAR), Next-Generation Radar (NEXRAD), Notice to Airmen (NOTAM), Pilot Report (PIREP), Special Use Airspace (SUA), Terminal Area Forecast (TAF), Wind/Temperature, and Lightning information. Each weather element could be toggled on and off independently by clicking on virtual buttons along the top of the display. Each weather element button had a separate time stamp that informed the user when each weather element was last updated on the presentation.

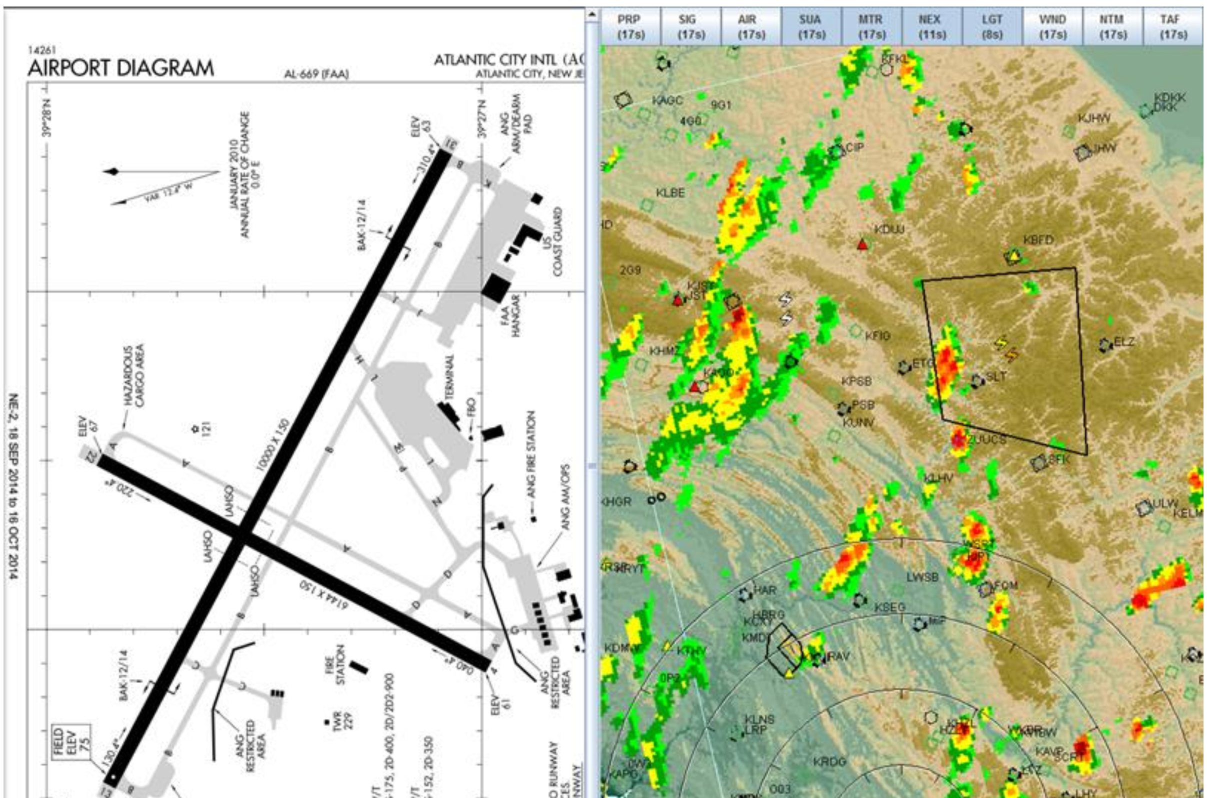



*Figure 3*. Weather presentation with the track-up configuration in "split" mode (airport diagram on the left side).

There was a separate touchpad cursor control (mounted in-between the cockpit seats) through which participants could interact with the display. Weather-elements graphics were clickable and used to toggle textual information dialog boxes for more in-depth information about conditions.

There were three distinct weather presentation backgrounds available to the participant: a Topological map (TOPO), a visual flight rules (VFR) aeronautical chart, and an instrument flight rules (IFR) aeronautical chart, selected by virtual buttons on the lower right of the display.

The participant could adjust the zoom level for the weather presentation. Three distinct zoom levels were available (as characterized in Table 2). The weather zoom distance was always displayed on a bar (in nmi) in the lower part of the display, between the range rings around the aircraft position symbol.

**Table 2. Zoom Levels of Weather Information Display**

| Zoom level | Nautical miles (nmi) per range ring | MAP width (nmi) | MAP height (nmi) |
|---|---|---|---|
| 1 | 5 | 40 | 60 |
| 2 | 20 | 160 | 240 |
| 3 | 50 | 400 | 600 |

### 2.3.4 Weather State-Change Notifications

During the simulation flight, we provided weather state-change notifications to participants in the experimental group. If information for METAR symbols, SUA outlines, or SIGMET outlines updated on the weather presentation during flight within a 100 nmi diameter around the aircraft position, the bracelet vibrated to notify the pilot of the change (see Figure 4). We chose to use vibration as a state-change notification because it does not compete with other sense modalities that pilots rely on during flight. For example, it is possible to use an auditory signal as a state-change notification, but this signal will compete with the auditory content of radio communications that pilots monitor during flight. Likewise, it is possible to use symbol or text notifications on the weather presentation as a means to provide state-change notifications. However, there is no guarantee that pilots will notice such notifications—especially considering the *change-blindness* phenomena found in the Phase 2 study.

*Figure 4*. Illustration of the vibrating bracelet.

During the initial briefing and the subsequent test flight, we instructed participants to observe the weather presentation immediately upon vibration and specifically look for relevant METAR, SUA, or SIGMET updates along the route of flight.

### 2.3.5 Stimulus Experiment System

We used the Stimulus Experiment System (SES) software to display the change-detection stimuli. This is the same system used in the change-detection experiment by Ahlstrom and Suss (2014). The SES allows the researchers to administer the experimental tasks to the participant by assigning a coded identifier to the participant and then automatically presenting a set number of experimental trials to the participant. Data (i.e., participants' responses) are recorded automatically and then written to a data file. The SES software is installed on Hewlett Packard desktop computers equipped with a Dell P2212H LCD monitor.

Similar to Ahlstrom and Suss (2014), we used a one-shot change-detection paradigm to assess each participant's ability to detect changes between two weather presentation images (i.e., Image 1 and Image 2) as illustrated in Figure 5.

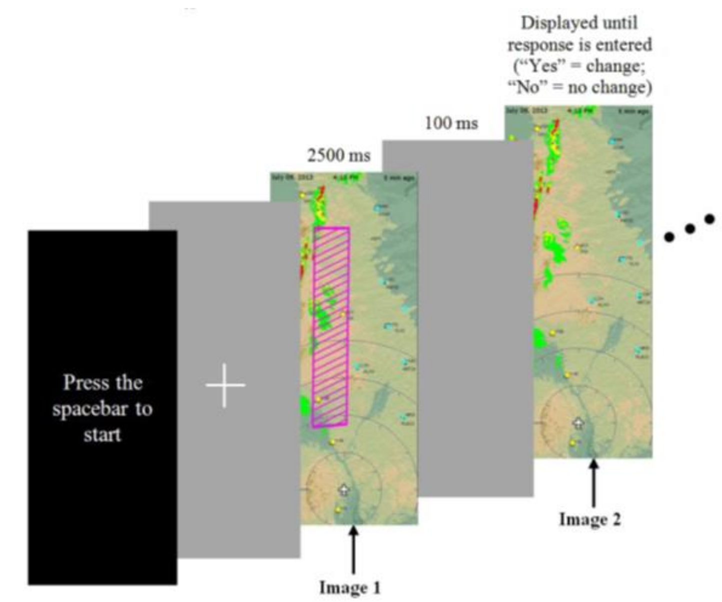



*Figure 5*. Illustration of the one-shot change-detection technique. Adapted from Rensink, 2002.

### 2.3.6 Functional Near-Infrared Spectroscopy

To assess participants' cognitive engagement during simulation runs, the Ahlstrom and Dworsky (2012) study and the Ahlstrom and Suss (2014) study used an objective fNIR recording during simulation flights. In this study, we used the same system during the simulation to record functional cortical activity during flight. The fNIR technology uses specific wavelengths of light to measure changes in the relative ratios of deoxygenated hemoglobin and oxygenated hemoglobin due to brain activity. The continuous-wave fNIR system is connected to a flexible forehead sensor pad that contains four light sources (peak wavelengths at 730 nm and 850 nm) and 10 detectors. This configuration generates a total of 16 measurement channels per wavelength. With two wavelengths and dark current recordings for each of the 16 channels, the system generates a total of 48 measurements for each 2 Hz sampling period.

### 2.3.7 Voice Communication System

The laboratory voice communication system provided a one-way link between the pilot and SME research personnel, who played the role of the pilot of the *aircraft following*.

The participant's microphone was continuously "live"; no Push-To-Talk (PTT) function was necessary. Pilot communications were recorded digitally as Windows Media Audio (WMA) files. The experimenter made written records of the times and contents of pilot communications for subsequent coding and analysis.

## 2.4 Procedure

In our study, we used a between-subjects design for the simulated flight. During the simulation, half of the participants wore a vibrating bracelet (experimental group) during flight while the other half (control group) flew without a bracelet. The purpose of the bracelet was to assess the effect of pilot decision-making and behavior from the use of weather state-change notifications (provided by bracelet vibrations).

For the change-detection experiment, we used a within-subjects design where each participant completed all experimental conditions. We counterbalanced the allocation of experimental versus control conditions across participants. Participants always performed the simulation flight before the change-detection experiment. Before the scenario flight, we informed the participants that they were part of a two-aircraft team ferrying an aircraft to the destination airport. Therefore, participants were required to communicate weather information to a simulated aircraft following.

Upon arrival at the simulation facility, each participant read and signed an informed consent form (Appendix A). Next, participants filled in a Background Questionnaire (Appendix B) and completed a self-paced PowerPoint briefing. The briefing contained information about the scenario's weather forecast, route, flight procedures, autopilot system, and an orientation of the cockpit weather presentation and weather data elements. At the end of the briefing, the SME demonstrated the basic aircraft controls and the cockpit console. The SME also instructed the participants about how to perform autopilot operations. Participants were instructed to employ the autopilot in cruise with Heading and Altitude modes on. After this briefing, the participants performed a practice flight (no data collection). During this practice flight, each participant was also instructed by the SME on the use of the weather presentation. Each participant was given sufficient practice time to become familiar with the use of the autopilot and the weather presentation. Before the start of each test flight scenario, each participant was fitted with the fNIR equipment and a communications headset; participants in the experimental condition were fitted with the vibrating bracelet. Participants were provided with an aeronautical chart with a plot of the filed route and labels identifying and giving the frequencies for the VORs used as waypoints (see Figure 6). The locations of the weather reporting stations nearest the destination airfield, KRSP and KRYT, were pointed out on the weather display (the stations are not depicted on the paper chart). Participants were instructed to maintain the flight within Visual Meteorological Conditions (VMC), deviating from the planned route if necessary. They were told that they could elect to divert to an alternate airfield should the situation warrant. Finally, they were reminded to communicate weather information and navigation instructions to the pilot who was following.

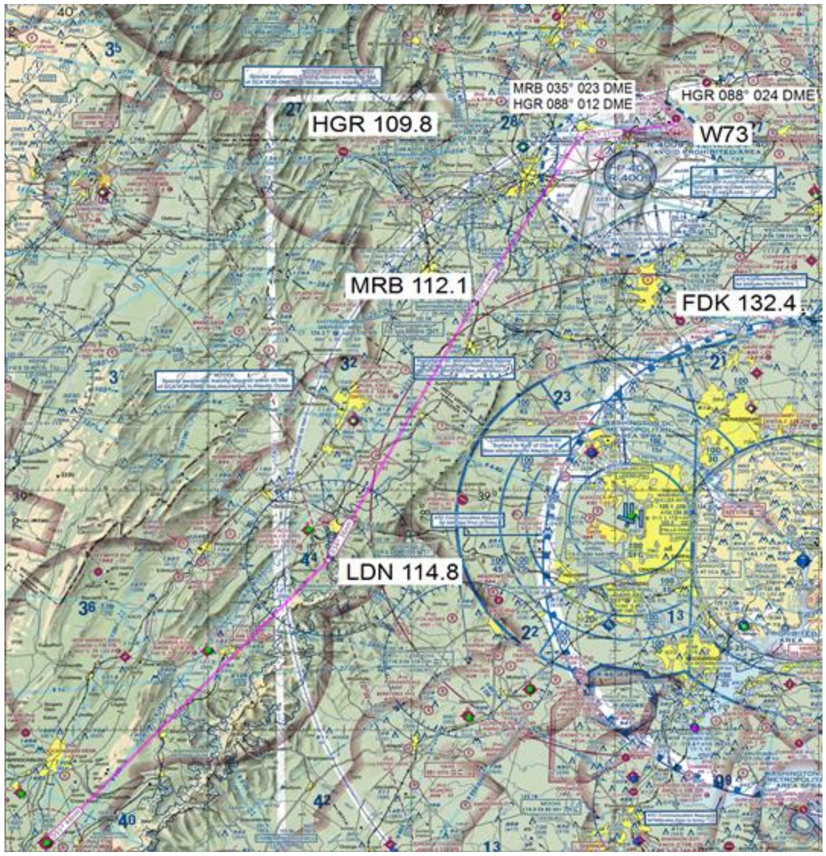



*Figure 6*. An illustration of the pre-planned route from Shenandoah Valley (KSHD) to Mid-Atlantic Soaring (W73).

At the end of the flight scenario, each participant completed a Post-Scenario Questionnaire (Appendix C). Following the completion of the questionnaire, the participant was given a short break before performing the change-detection part-task. At the end of the part-task experiment, the research team debriefed the participant.

### 2.4.1 Flight Scenarios

The scenario involved a pre-planned VFR flight from Shenandoah Valley (KSHD) → Linden (LDN) → Martinsburg (MRB) → MRB 035° 23 DME → W73 (Mid-Atlantic Soaring) as shown in Figure 6. Two weather reporting stations near the destination airfield: KRYT is W of W73, 3.9 nmi distant on a 259-degree bearing; KRSP is SW of W73, 8.4 nmi distant on a 229-degree bearing. At the scenario start-up, the graphical METARs for both KRSP and KRYT were indicating VFR flight conditions (blue). Figure 7 illustrates the weather condition viewed from the cockpit out-the-window view.

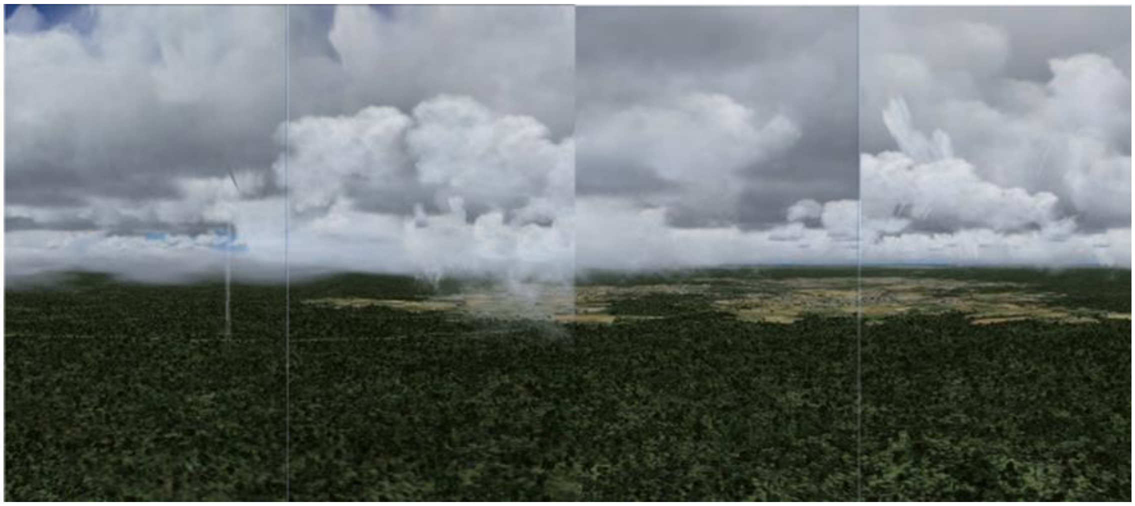
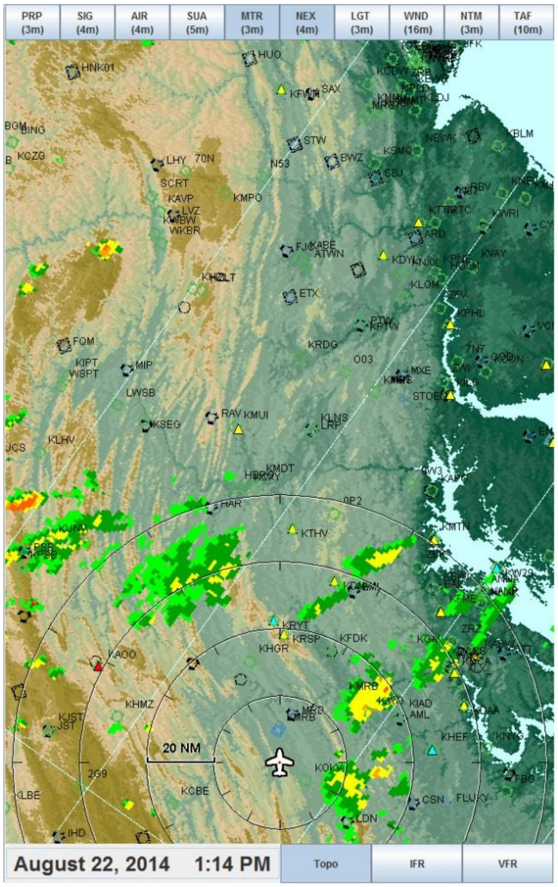


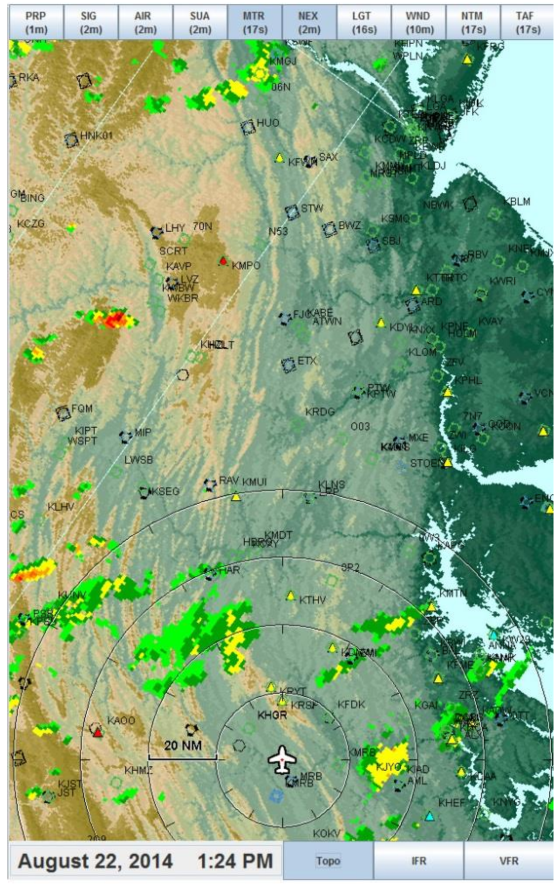
*Figure 7.* An illustration of the VMC conditions at scenario start-up (The illustration was created by stitching together screen captures from four separate monitors and is therefore not properly aligned in the figure.).

For the pre-planned route, all waypoints were outside the prohibited airspace P-40 surrounding Camp David, and the restricted airspace R-4009 was not active during the time of flight. Participants commenced the scenario in the cruise phase at an altitude of 6,000 ft.

The VFR flight was affected by METAR changes at 14 minutes (KRSP) and 24 minutes (KRYT) into the flight (as illustrated in Figure 8). During flight, the experimental group received METAR state-change notifications for KRSP and KRYT via the vibrating bracelet. The control group did not receive any METAR state-change notifications.




At 14 min into the scenario, the METAR at KRSP changed its flight category color from VFR (blue) to IFR (yellow).




At 24 min into the scenario, the METAR at KRYT changed its flight category color from VFR (blue) to IFR (yellow).

*Figure 8*. METAR changes at 14 min and 24 min into the scenario. Each change triggered a bracelet vibration for the experimental group.

### 2.4.2 Simulation – Weather State-Change Notifications

During the simulation, the experimental group was equipped with a vibrating bracelet. The bracelet provides a weather state-change notification (vibration) if METAR, SIGMET, or SUA information was updated anywhere inside a circular area around the current aircraft position (100 nmi diameter).

#### *2.4.2.1 Independent variable*

The only independent variable was the presence of weather state-change notifications provided by a vibrating bracelet.

#### *2.4.2.2 Dependent variables*

During the simulation flights, we recorded data in six dependent variable categories (see Table 3).

**Table 3. Simulation Dependent Measures**

| Number | Dependent variable | Description |
|---|---|---|
| 1 | Flight profile measures | The altitude changes and deviation from the pre-planned route. Proximity distance to the prohibited airspace P-40 surrounding Camp David. |
| 2 | Weather situation awareness (WSA) | The participants' communication of weather information to the second aircraft. |
| 3 | Decision-making | The participants' decision to deviate from the pre-planned route and/or to divert to an alternate airport. |
| 4 | Cognitive engagement | The blood oxygenation changes captured by the fNIR system (i.e., the system analyzes increases and decreases of oxygenated hemoglobin, which correlates with changes in cognitive engagement). |
| 5 | Weather presentation interaction | The participants' interactions with the weather presentation (i.e., changing zoom levels, reading METAR and TAF text, turning weather elements on and off, and the durations pilots used the VFR, IFR, and Topological backgrounds). |
| 6 | Distance to weather | The distance from the aircraft to areas of > 30 dBZ precipitation. |

### 2.4.3 Derivation of Flight Path, Deviation, and Distance-to-Weather Measures

The weather scenarios in the present study contained different weather patterns that might affect pilot behavior. For example, one scenario contained convective activity and areas of low ceiling and low visibility. We measured the distance from the aircraft location (i.e., latitude/longitude) to the closest point of approach for ≥ 30 dBZ precipitation cell intensities (visualized as yellow pixels) at 1-minute intervals. For all scenario flights, we also recorded the aircraft's position (in 10-second intervals) relative to the pre-planned route.

Because we used prerecorded weather scenarios, we did not have access to the latitude/longitude position data for each weather element and symbol location. To circumvent this issue, we used C++ to program an automated evaluation tool that loaded and evaluated weather screenshots and recorded log files from the scenarios. We used several defined parameters for the analyses. Our aircraft log files contained, among other data parameters, the elapsed scenario time in seconds, latitude, longitude, altitude, and heading. In a first step, the evaluation algorithm extracted all coordinates for each time interval (2 Hz) and saved them in a vector. Second, the algorithm loaded the scenario data with all the defined route points along with their latitude/longitude values. Third, the algorithm computed all distances in nautical miles, $\mathrm{d}$, between latitude/longitude points as a great circle distance using the spherical law of cosines. This equation serves as a simple alternative to the haversine formula, sufficient for our computations due to the short scenario distances:

$$\mathrm{d} = \mathrm{acos}(\sin(\mathrm{latA}) \cdot \sin(\mathrm{latB}) + \cos(\mathrm{latA}) \cdot \cos(\mathrm{latB}) \cdot \cos(\mathrm{lonB} - \mathrm{lonA})) \cdot 3440.065.$$

During the calculation, the algorithm assessed whether a perpendicular latitude/longitude point was on the defined route segment and whether the great circle distance between the aircraft position and the perpendicular point was smaller than the shortest vector distance. If true, the algorithm updated the location value. This implies that equidistant path deviations were calculated between the blue path and all the hypothetical red aircraft positions as illustrated in Figure 9.

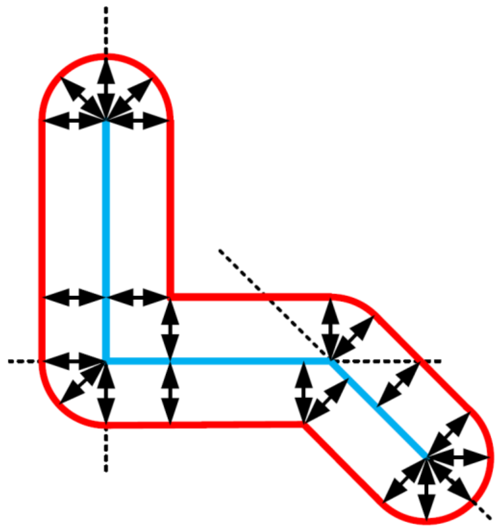


*Figure 9.* Illustration of equidistant deviation points (red) from a defined route (blue).

In an initial step, the algorithm selected the shortest distance between the aircraft position and each route point to derive a path deviation. Subsequently, the algorithm computed the distances between aircraft positions and route segments using two neighboring route points. This calculation determined the space between the aircraft point and an infinite line going through both route segment points. This implied that the algorithm had to assess whether the resulting perpendicular point was based on the infinite line that was part of the route segment or whether it was located on one of the two adjacent line sections. If the perpendicular point was located on the defined route segment, and the great circle distance between the aircraft position and the perpendicular point was smaller than the actual shortest vector distance, the algorithm assigned a new value to the aircraft position.

To allow for distance calculations to weather areas, we identified all relevant coordinates for weather cell intensities. We performed this by identifying display pixel locations for weather cells and airport locations and triangulated these with display pixel locations for published airport latitude/longitude coordinates. This required scenario screenshots from the weather application for every minute of the weather scenario. The algorithm analyzed these images and determined the location of the yellow weather pixels. These pixel values—with a given Red, Green, Blue (RGB) value—were stored in a vector for subsequent use in the calculation of distances to aircraft coordinates. Following the outlined procedure, the algorithm produced the shortest distances between aircraft and weather cells for each minute of the scenario.

### 2.4.4 Data Analysis

We used Bayesian estimation to analyze data from the current study as outlined in Ahlstrom and Suss (2014). This analysis framework uses Bayesian estimation with Markov Chain Monte Carlo (MCMC) sampling to determine the posterior distribution of parameters for outcomes such as means, standard deviations, and effect sizes. During the analysis, we used JAGS ("Just Another Gibbs Sampler"; Plummer, 2003, 2011) that we called from R (R Development Core Team, 2011) via the package rjags. All software for the analysis and figure generation is adapted program code from Kruschke (2015).

The Bayesian analysis framework generates a posterior distribution, which is a distribution of credible parameter values. We can use this large distribution of representative parameter values to evaluate various parameters or to compare differences between parameter distributions. Here, we use a separate decision rule to convert our posterior distributions to a specific conclusion about a parameter value. When plotting the posterior distribution, we include a black horizontal bar that represents the 95% High Density Interval (HDI). The HDI is a very important concept for the forthcoming analyses. This is because every value inside the HDI has a higher probability density compared to values that fall outside the HDI. When we compare conditions, we compute differences at each step in the MCMC chain and present the result in a histogram with the HDI. These histograms show both credible differences and the uncertainty of the outcome. If the value 0 (implying zero difference) is not located within a 95% HDI, we say that the difference is credible. If the 95% HDI includes the value 0 the difference is not credible as it means that a difference of 0 is a possible outcome.

We are also showing a Region of Practical Equivalence (ROPE) in the histograms. The ROPE contains values that, for all practical purposes, are the same as a null effect. If the 95% HDI falls completely within the ROPE margins for an effect size, we can declare the presence of a null effect, and unlike traditional analyses, we can accept the null outcome. If, on the other hand, the entire ROPE falls outside the 95% HDI for an effect size, we can reject the presence of a null effect.

For all analyses, we used 1,000 steps to tune the samplers and 2,000 steps to burn-in the samplers, while running 3 chains and saving every step in the chain (i.e., we used no thinning). To derive the posterior distributions, we used 200,000 samples. For all analyses, we use priors that are vague and noncommittal on the scale of the data.

## 3. RESULTS

### 3.1 Flight Profile Measures

#### 3.1.1 Altitude Changes

To assess participants' flight behavior when avoiding clouds at altitude and when avoiding reduced ceiling and visibility conditions along the route, we analyzed participants' vertical and horizontal flight profile. The vertical flight profile was captured by analyzing participants' altitude changes. The horizontal flight profile was captured by analyzing participants' deviations from the pre-planned route.

We used a dependent measure of altitude change where we first computed a difference score between the recorded altitudes for each second of the scenario with the altitude at scenario start-up (6,000 ft). We then averaged each participant's difference scores and used one difference score per participant for the analysis. We used a Bayesian model (Kruschke, 2015; p. 449) for a *metric-predicted* variable (i.e., altitude in feet) for two groups (experimental vs. control).

Figure 10 shows the altitude data (top), posterior group means (middle), difference of means (bottom left), and the effect size (bottom right) for the altitude comparison between the control group and the experimental group. On average, the control group had larger altitude variations (mode = –858 ft) than the experimental group (mode = –570 ft). However, as is shown in the posterior distribution for the difference means (mode = 287 ft; bottom left), the value 0 is included at the left end of the 95% HDI. Because of this, we cannot unequivocally say that the difference of means is credible. After all, a difference of 0 is one of the possible outcomes, but with a very small likelihood. Likewise, the effect size (bottom right) with a mode of 0.416 also has the value 0 included at the left end of the 95% HDI, and is therefore not credible.

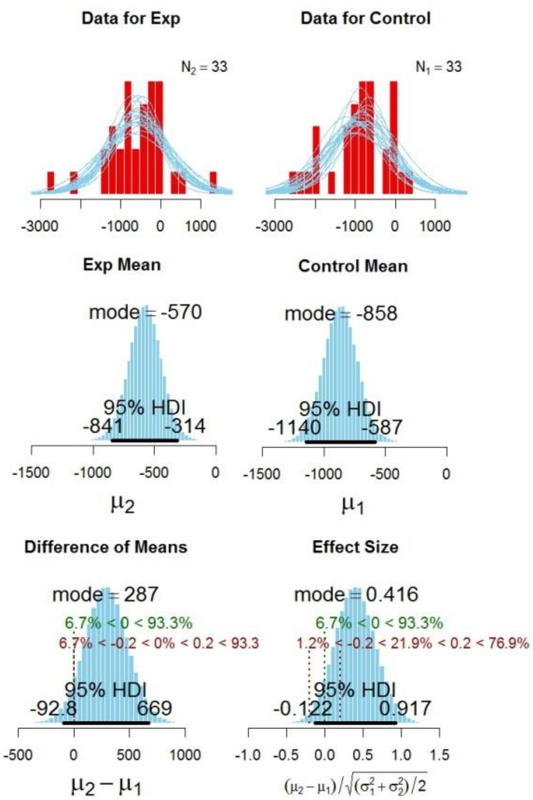



*Figure 10.* Data (top) and posterior distributions for means (middle), difference of means (bottom left), and effect size (bottom right) for the comparison of altitude changes between the experimental group and the control group.

During flight the experimental group received weather-state notifications regarding METAR changes at 14 minutes (KRSP) and 24 minutes (KRYT) into the flight. Potentially, the METAR state-change notifications could have prompted participants to adjust their altitude based on new visibility and ceiling information. Therefore, we made a separate analysis of the altitudes starting at 14 minutes into the flight. Figure 11 shows the result for the altitude comparison between 14 min and 40 min. into the scenario. On average, the control group had larger altitude variations (mode = –1,280 ft) than the experimental group (mode = –873 ft). However, the value 0 is included in the 95% HDI for the difference of means (bottom left; mode = 411 ft) and the effect size (bottom right; mode = 0.413). Therefore, neither the difference of means nor the effect size is credible.

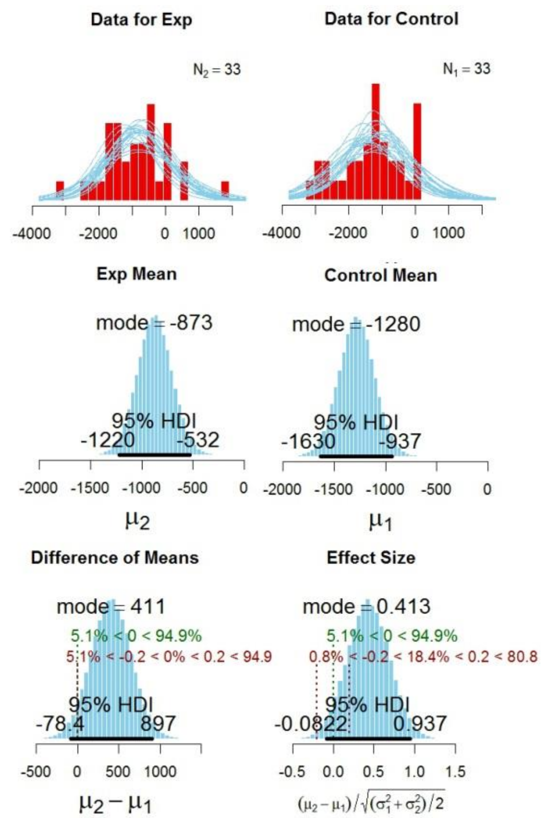



*Figure 11*. Data (top) and posterior distributions for means (middle), difference of means (bottom left), and effect size (bottom right) for the comparison of altitude changes from 14 minutes to 40 minutes into flight between the experimental group and the control group.

### 3.1.2 Deviations from the Pre-planned Route

We recorded each participant's deviation from the pre-planned route every 10 seconds during the flight. This yielded 240 deviation scores for each participant and flight. We then averaged each participant's deviation scores and used one deviation score per participant for the analysis. Here, we also used a Bayesian model (Kruschke, 2015; p. 449) for a metric-predicted variable (i.e., deviation in nmi) for two groups (experimental vs. control).

Figure 12 shows the comparison of the mean route deviations for the control group and the experimental group. The mean deviations are similar for both groups, with a posterior mode of 2.17 nmi for the control group and 2.37 nmi for the experimental group. The difference of means and the effect size have modes of 0.192 and 0.149, respectively—neither of these outcomes is credible as the value 0 is located within the 95% HDIs.

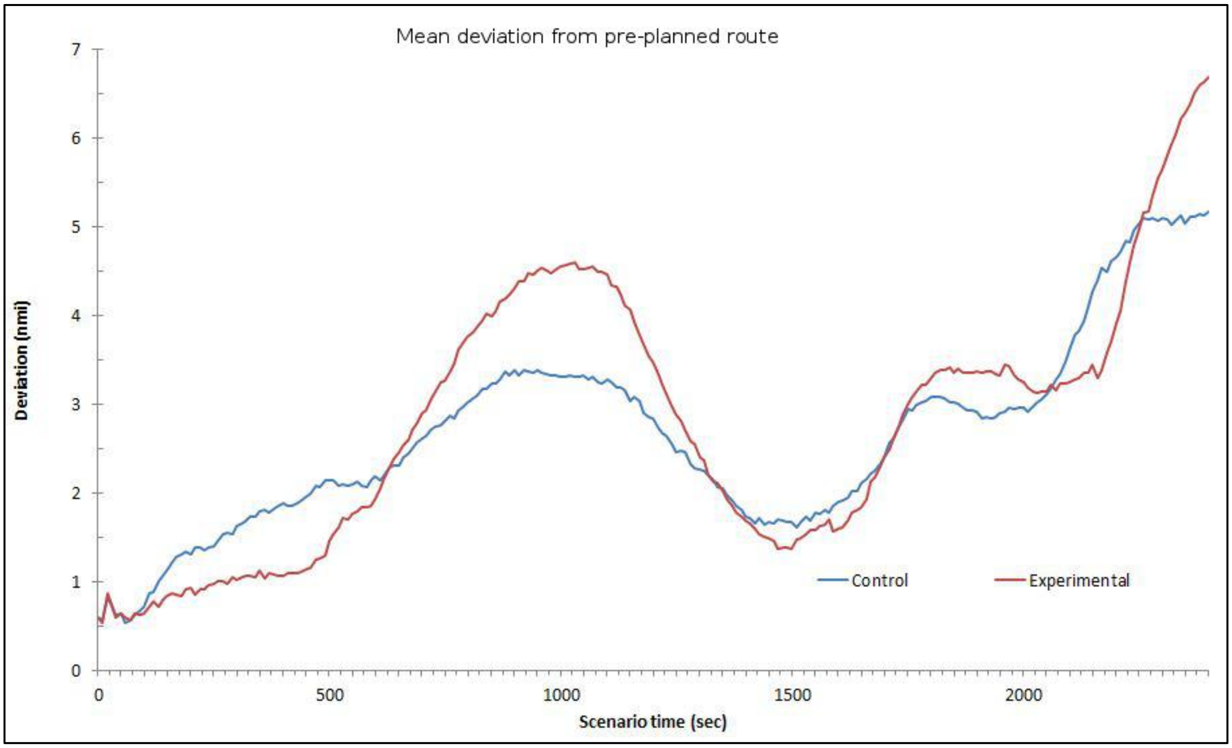



*Figure 12.* Mean deviation from the pre-planned route for the experimental group and the control group.

The pre-planned route was designed to keep the flights clear of the prohibited airspace (P-40) surrounding Camp David. However, route deviations at the end of the scenario could have placed aircraft in close proximity to P-40. To assess the proximity between the aircraft and the P-40 area, we used a calculated average distance from the aircraft to P-40 for each minute (per participant) of the last 10 minutes of the scenario. We found that the groups were flying equally close to the P-40 area, with a posterior mode for the control and experimental group of 8.66 nmi and 8.56 nmi, respectively. This yields a posterior difference of means with a mode of –0.224, which is not credible because the 95% HDI (–2.26 to 1.96) included the value zero.

Although the control group and the experimental group, on average, flew equally close to the P-40 area, the analysis revealed two P-40 violations in the experimental group that occurred at 33 min and 40 minutes into the scenario. In both cases, it was a clear violation with a 0.3 nmi and a 1.5 nmi penetration within the P-40 airspace.

To summarize, there were no credible differences in the vertical and horizontal flight profiles between the experimental group and the control group. There are also no credible differences between groups in how close participants flew to the P-40 area. However, there were two P-40 airspace violations in the experimental group but there were no violations in the control group.

### 3.1.3 Weather Situation Awareness

One of the four hypotheses explored in this study is that weather state-change notifications will result in earlier and more accurate pilot recognition of weather state changes. This, in turn, will positively affect pilot WSA, defined as a pilot's combined perception of time, current weather distribution along the planned route and alternative routes, areas free of hazardous weather, weather locations in the near future, and the use of alternative routes to avoid hazardous weather. A high

WSA would imply that a pilot is cognizant of and prepared for weather-state changes and will therefore have more time to take appropriate action. Early decision-making to avoid weather will also result in pilots keeping appropriate distances from weather events.

During the simulation participants were part of a two-aircraft team ferrying an aircraft to the destination airport. Participants were instructed to communicate weather information and flight decisions to the second pilot. We logged all communications and combined each relevant message into five main categories (see Table 4).

**Table 4. Communication Category Descriptors**

| Category | | | | |
|---|---|---|---|---|
| **Weather data** | **Weather direct view** | **Ground view** | **Maneuver/course change** | **Other** |
| - Providing METAR, TAF information, etc.<br>- Describing weather on the cockpit weather presentation.<br>- Reporting weather-state changes. | - Precipitation.<br>- Visibility.<br>- Ceiling.<br>- Unusable altitude.<br>- Clear of weather.<br>- Avoiding weather.<br>- Encountering weather.<br>- VFR conditions.<br>- Loss of VFR conditions.<br>- Weather in sight.<br>- Cloud location. | - Report terrain.<br>- Landmark in sight.<br>- Landmark not found.<br>- Airfield in sight.<br>- Airfield not sighted. | - Diverting to alternate airfield.<br>- Increasing/decreasing speed.<br>- Flying direct-to (bypassing waypoint).<br>- Adding waypoint.<br>- Turning left/right.<br>- Turning to heading.<br>- Climbing.<br>- Descending.<br>- Leveling. | - Position.<br>- Heading.<br>- Course.<br>- Altitude.<br>- Intent.<br>- On/off course.<br>- Navigation problem.<br>- Nonspecific reports. |

*Note.* METAR = Meteorological Aerodrome Report; TAF = Terminal Area Forecasts; VFR = Visual Flight Rules.

The first category in Table 4, Weather data, captures all communication related to providing weather information—such as METAR, TAF, and the communication of information and weather state-changes acquired from the cockpit weather presentation. During the scenario, both groups had access to the same weather presentation. The second category, Weather direct view, captures communicated weather information acquired from the out-the-window view. The third category, Ground view, captures communicated information associated with terrain, landmarks, and airfields. The fourth category, Maneuver/course change, captures communications related to decisions about maneuvering the aircraft, diverting, and changing course. The last category, Other, encompasses communicated information about position, heading, altitude, intent, and other nonspecific reports (e.g., "We're OK now.").

Figure 13 (left) shows the relative frequencies for the communication of Weather data information for the experimental group and the control group. The communication counts are from start-up to the end of the scenario. Because the analysis involves a predictive value that is a count (i.e., the number of communications), we used a model by Kruschke (2015; p. 703) for analysis of data on a count-valued measurement scale.

As we can see in Figure 13 (left), the count of Weather data communications is higher for the experimental group than for the control group. The experimental group has a total of N = 162 communications to the aircraft following, versus N = 115 for the control group. The posterior difference (mode = 0.331) is credible because the value 0 is outside the 95% HDI (right).

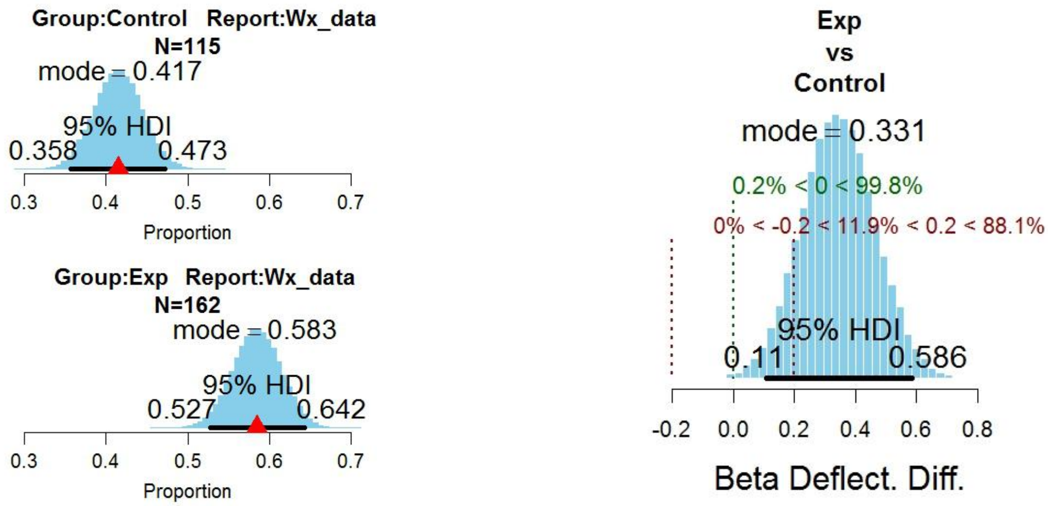



*Figure 13*. Posterior distributions (left) for the estimated cell proportions for the communication of **Weather data** for the experimental group and the control group. The Weather data counts are from the entire scenario (40 min).The triangles at the bottom of the histogram indicate the actual proportions for each group. The histogram to the right shows the posterior contrast for the comparison (experimental-control).

The experimental group provided credibly more Weather data communications than the control group when measured during the entire scenario. What we would like to assess is whether the propensity of communicating weather data for the experimental group is affected by the weather state-change notifications. To assess this possibility, we analyzed the Weather data communications starting at 14 min into the scenario (at the first METAR state-change notification). Figure 14 shows the relative frequencies for the communication of Weather data information for the experimental group and the control group from 14 min to the end of the scenario.

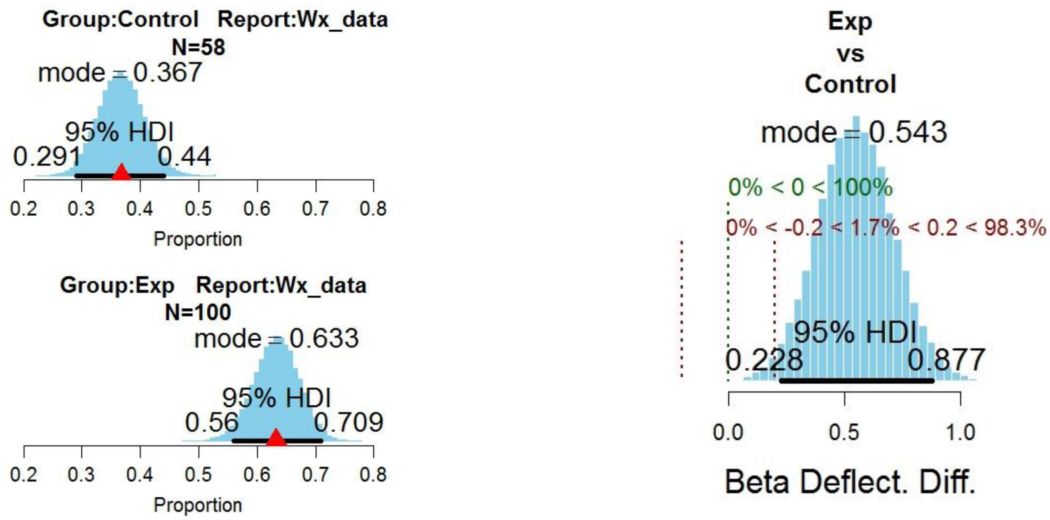



*Figure 14*. Posterior distributions (left) for the estimated cell proportions and the posterior difference (right) for the communication of **Weather data** for the experimental group and the control group. The Weather data counts are from 14 min into the scenario to the end of the scenario (40 min).

As we can see in Figure 14 (left), the count of Weather data communications is higher for the experimental group (N = 100) than for the control group (N = 58). The posterior difference (mode = 0.543) is credible because the value 0 is outside the 95% HDI (right). Evidently, weather state-change notifications improved the WSA for participants in the experimental group, resulting in more Weather data information to the aircraft following.

Figure 15 (left) shows the relative frequencies for the communication of Weather direct view information for the experimental group and the control group. The communication count is lower for the control group (N = 373) compared to the experimental group (N = 427). Looking at the posterior contrast (right), we see that the mode is 0.14, with the 95% HDI spanning from –0.00323 to 0.274, thereby barely including the value 0. Therefore, while the result supports the inference that the experimental group communicated more Weather direct view information to the aircraft following compared to the control group, we cannot unequivocally state that the difference is credible because a difference of 0 is possible albeit with a very low probability.

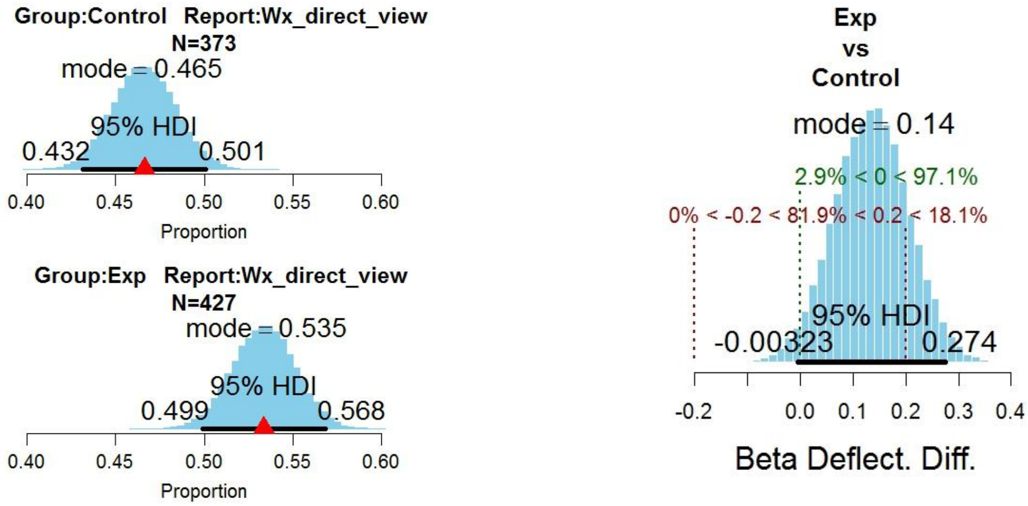



*Figure 15*. Posterior distributions (left) for the estimated cell proportions and the posterior difference (right) for the communication of **Weather direct view** information for the experimental group and the control group.

Figure 16 (left) shows the relative frequencies for the communication of Ground view information for the experimental group and the control group. The total count of Ground view reports for the control group (N = 78) and the experimental group (N = 72) is very similar. The posterior distribution (right) reflects this outcome and shows no credible difference with the value 0 included in the 95% HDI.

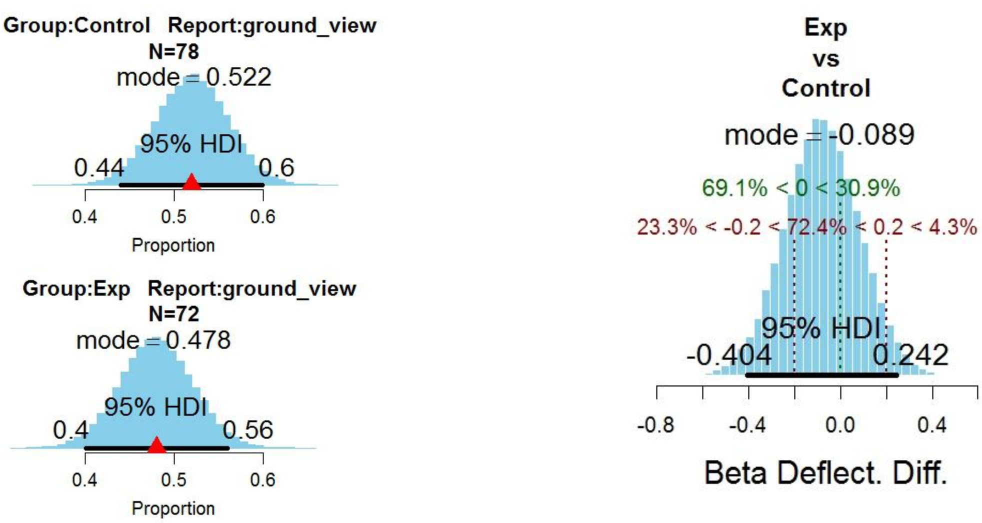



*Figure 16*. Posterior distributions (left) for the estimated cell proportions and the posterior difference (right) for the communication of **Ground view** information for the experimental group and the control group.

Figure 17 (left) shows the relative frequencies for the communication of Maneuver/course change information for the experimental group and the control group. There is a higher count for the experimental group (N = 411) compared to the control group (N = 330). The posterior contrast (right) shows the difference as credible, with the value 0 outside the 95% HDI.

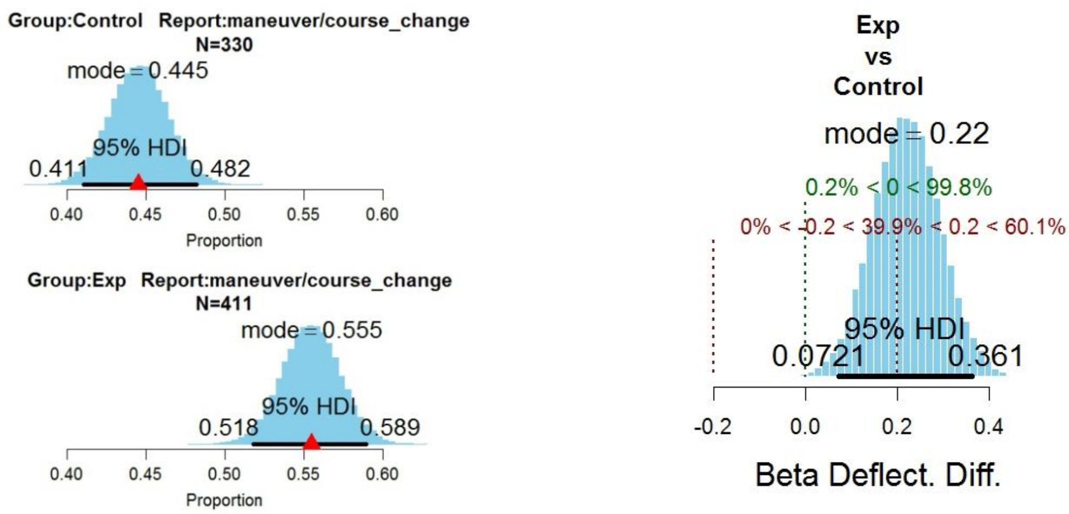



*Figure 17*. Posterior distributions (left) for the estimated cell proportions and the posterior difference (right) for the communication of **Maneuver/course change** information for the experimental group and the control group.

Finally, Figure 18 (left) shows the relative frequencies for the communication of Other information for the experimental group and the control group. The communication count is higher for the control group (N = 687) compared to the experimental group (N = 604). The posterior contrast (right) shows this difference as credible, with the value 0 outside the 95% HDI.

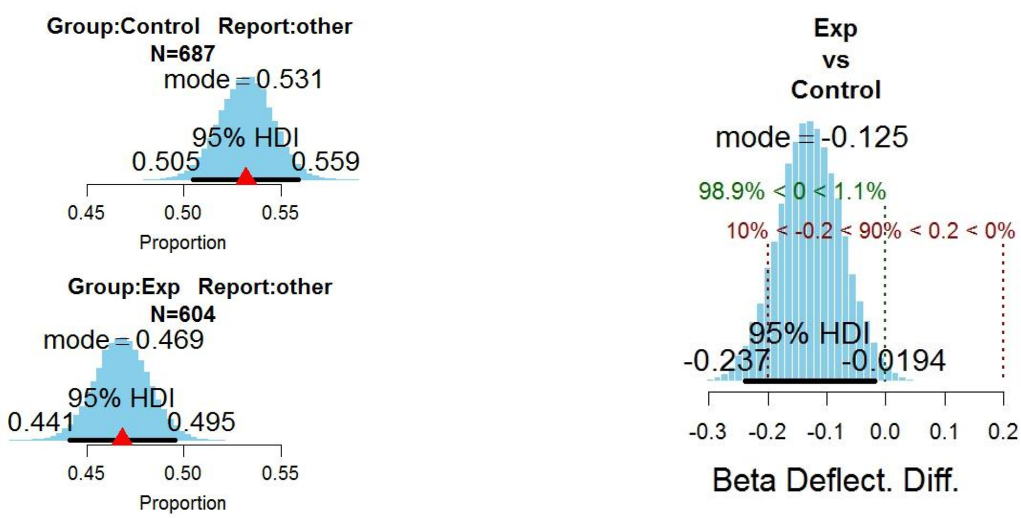



*Figure 18*. Posterior distributions (left) for the estimated cell proportions and the posterior difference (right) for the communication of **Other** information for the experimental group and the control group.

To summarize, the experimental group receiving weather state-change information provided credibly more communications of Weather data information and Maneuver/course change information than the control group. The experimental group also provided a higher count of communications of Weather direct view information. There is no credible difference in the communication of Ground view reports between the groups. Only for the communication of Other information did the control group provide a credibly higher count of reports than the experimental group. Taken together, this supports our hypothesis that weather state-change notifications will result in earlier and more accurate pilot recognition of weather state changes and positively affect pilot WSA.

### 3.1.4 Distance to Weather

The use of cockpit weather applications could potentially increase pilot WSA and enhance weather avoidance behavior. Current guidelines by Federal Aviation Administration (FAA) and NOAA (1983) state that hazardous weather should be avoided by at least 20 statute miles (i.e., 17.379 nmi). During a weather avoidance simulation, Ahlstrom and Dworsky (2012) measured the distance-to-weather (≥ 30 dBZ precipitation cells) and found that GA pilots flew closer than the current guidelines with a mean distance-to-weather of 14 nmi.

In this study, we measured (once a minute) the distance-to-weather (≥ 30 dBZ cells) to assess pilot weather avoidance behavior. For the distance-to-weather analysis, we first averaged the 40 distance measures for each participant and used one mean value per participant for the analysis. We used a Bayesian model (see Kruschke, 2015; p. 449) for a metric-predicted variable (i.e., distance in nmi) for two groups (experimental vs. control). Figure 19 shows the mean distance-to-weather (actual data) for the control group and the experimental group.

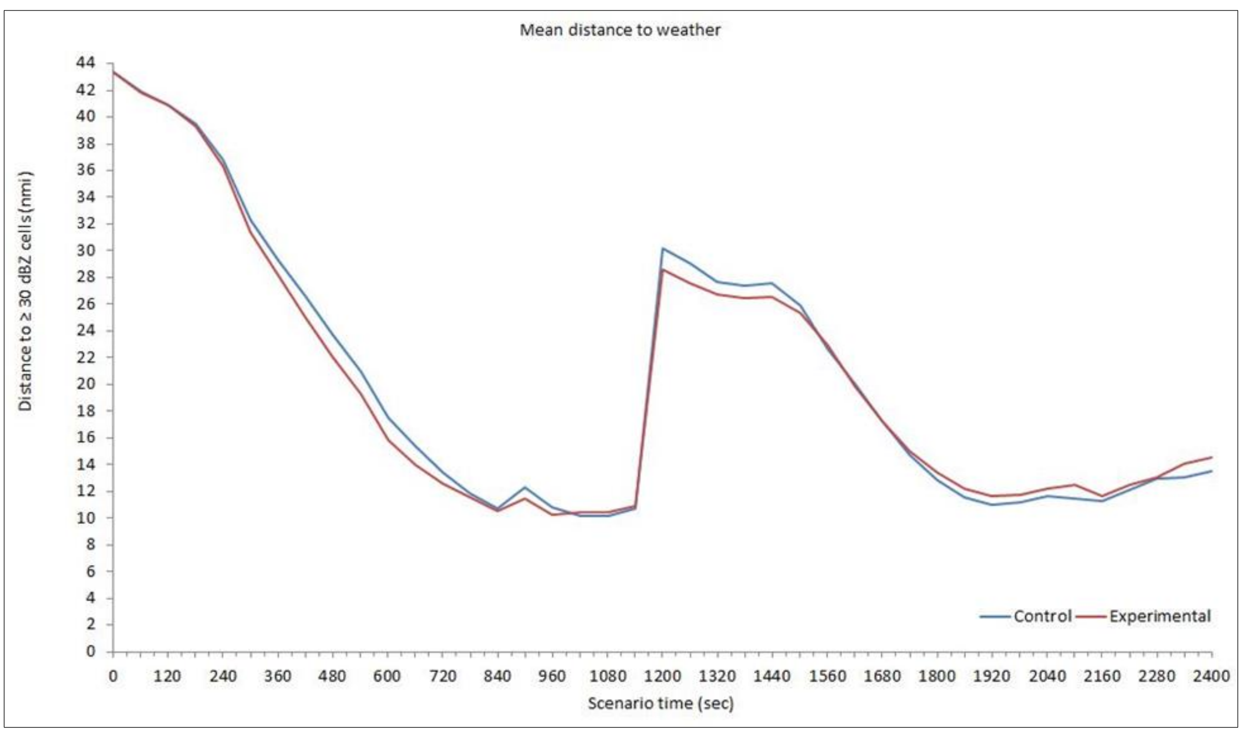



*Figure 19*. Mean distance-to-weather for the experimental and control group groups.

The analysis revealed posterior means that are very similar for both groups, with a predicted mode of 20 nmi for the control group and 20.2 nmi for the experimental group. This difference of means (mode = 0.27) is not credible as the value 0 is located within the 95% HDI. However, there was a credible difference of means (mode = 0.27) in the SD parameter where the control group (mode = 4.49) had larger intra-group variation than the experimental group (mode = 2.62). This means that although the group participants, on average, flew the same distance away from the weather, there was more variation in the distance-to-weather for the control group.

Besides assessing the average distance-to-weather, we also assessed the closest distance that participants came to 30 dBZ cells. This analysis showed that both groups were very similar, with a mean posterior closest distance of 5.29 nmi and 4.89 nmi for the control and experimental group, respectively. The posterior difference of these means is not credible as the value 0 is included in the 95% HDI. The result of the distance-to-weather analyses shows that both groups kept similar distances to 30 dBZ cells. However, the outcome also reveals that participants in both groups flew much more closely to hazardous weather than what is recommended in current guidelines.

### 3.2 VFR Flight into IMC

In VFR flight into IMC conditions, pilots inadvertently enter clouds or haze where they no longer can see the horizon or the terrain. At best, these encounters are very brief, or they can easily be countered by altitude or heading changes. At worst, the pilot can experience spatial disorientation and lose control of the aircraft (Wilson & Sloan, 2003). In the present simulation, no participant entered IMC and lost control of the aircraft. However, participants reported "Loss of VFR conditions" as they entered smaller cloud formations or haze in the vicinity of storm cells. Figure 20 shows the frequency counts of reported Loss of VFR conditions for the control group and the experimental group. Of the total of 60 counts in the figure, only one occurred before 14 min into the scenario. The remaining frequency counts of reported Loss of VFR conditions occurred, on average, around 30.5 min into the scenario and was the same for both groups.

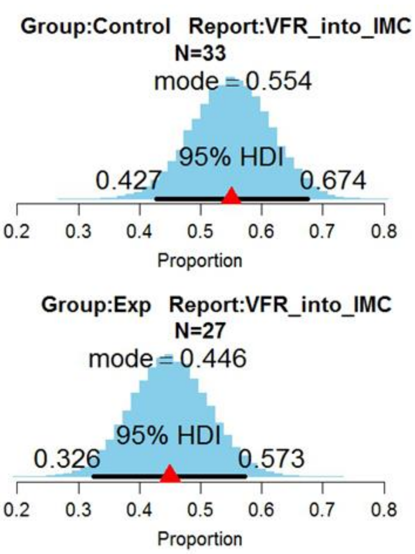



*Figure 20.* Posterior distributions for the estimated cell proportions for **Loss of VFR conditions** for the experimental group and the control group.

Because the analysis involves a predictive value that is a count (i.e., the number of reported Loss of VFR conditions), we used a model by Kruschke (2015; p. 703) for analysis of data on a count-valued measurement scale. As shown in Figure 20, there are more reports of Loss of VFR conditions in the control group (N = 33) than in the experimental group (N = 27). However, the difference is not credible as the posterior distribution of the difference (mode = –0.215) includes the value 0.

The participants in both groups who reported Loss of VFR conditions had a very similar flight background. There was only one participant in the control group without any instrument hours compared to two participants in the experimental group. The mean number of instrument hours were 3,103 hours for the control group and 3,118 hours for the experimental group. The median age of 58 years for the two groups was identical.

To summarize, there are no credible differences between the experimental group and the control group regarding the average distance-to-weather or the closest distance-to-weather. Furthermore, there are no credible differences between groups with regards to VFR flight into IMC.

### 3.2.1 Decision-Making

We assessed the simulation time at which participants announced their decision to divert to an alternate airport due to weather. Out of 36 participants in the control group, 19 participants decided to divert. Of the 33 participants in the experimental group, 20 participants decided to divert. The mean decision time (actual data) for the control and experimental groups was 28.5 minutes and 32.06 minutes, respectively. An analysis using a model (Kruschke, 2015; p. 449) for a metric-predicted variable (i.e., scenario time in minutes) between the experimental and the control group showed that the difference of means (mode = 2.71 min) for the decision time to divert was not credibly different, because the value 0 was included in the 95% HDI (ranging from –1.76 to 7.48).

### 3.2.2 Weather Presentation Interaction

During the simulation, we recorded how participants interacted with the weather presentation. From these recordings, we analyzed what background maps and weather elements the participants were using and for how long each element was displayed. The weather application allowed participants to select one of three different backgrounds: VFR and IFR flight charts and a topological map. The total duration (sec), during which each background was displayed by each participant, was analyzed using a Bayesian split plot design for a metric-predicted variable (Kruschke, 2015; p. 610) with one within-subjects factor (map background) and one between-subjects factor (experimental group vs. control group). We found a credible main effect of map background, with the topological map being displayed longer than both the VFR and IFR charts (posterior mode = 1,270 s, 95% HDI = 1070, 1510), but we found no credible difference between groups (posterior mode = –5 s, 95% HDI = –207, 191) and no credible interaction of map type with group (posterior mode = 4 s, 95% HDI = –293, 389).

Ahlstrom and Suss (2014), using the same METAR symbols as used in the present simulation, found that pilots had a difficult time seeing when a METAR symbol changed its flight category color from VFR (blue) to IFR (yellow). In fact, pilots only detected 25% of all the METAR changes. This had the implication that pilots who failed to detect the METAR changes were more likely to continue their VFR flight towards the pre-planned destination without good WSA. As a consequence, pilots continued their flight without being aware of weather changes at their destination airport that implied reduced ceiling and reduced visibility.

By providing METAR state-change notifications, we can alert the pilot of important weather changes. This results in earlier and more accurate recognition of weather state-changes and improves participant WSA and decision-making.

During flight, participants could activate (cursor click) a METAR station symbol and view a window with METAR text, TAF, Winds/Temps aloft, and NOTAM information. Of particular interest for our analysis is the interaction with METARs from 14 min to the end of the scenario. At 14 min into the scenario, the METAR at KRSP changed its flight category color from VFR (blue) to IFR (yellow). At 24 min into the scenario, the METAR at KRYT changed its flight category color from VFR (blue) to IFR (yellow). At both of these instances, the experimental group received a weather state-change notification (vibration) from the bracelet.

The analysis of METAR interactions involves a predictive value that is a *count* (i.e., the number of METAR activations), and we therefore used a model by Kruschke (2015; p. 703) for analysis of data on a count-valued measurement scale. Figure 21 shows the interaction counts for the KRSP METAR station for the control group and the experimental group. There is a higher count for the experimental group (N = 60) compared to the control group (N = 36). As shown by the posterior distribution (right), this difference is credible (mode = 0.527) as the value 0 is not included in the 95% HDI. Evidently, the state-change notification alerted participants to the updated METAR information which resulted in a higher count of METAR interactions for the experimental group.

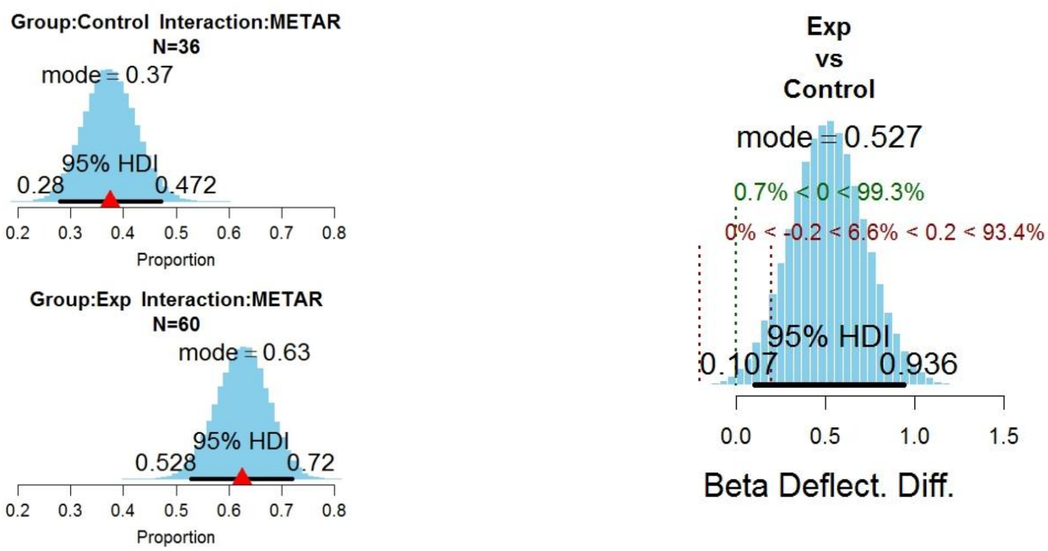



*Figure 21.* Posterior distributions (left) for counts and estimated cell proportions for KRSP METAR interactions and the posterior difference (right) between the experimental group and the control group.

At 24 minutes into the scenario, the METAR at KRYT changed its flight category color from VFR (blue) to IFR (yellow). However, due to a programming error, "clicks" on KRYT were not recorded as such, but only as clicks on a latitude/longitude position. Therefore, no METAR window was displayed for KRYT since the click was not correctly identified by the software. In post-processing, we classified a METAR interaction as any cursor click within 3 km at scale of KRYT as a click on KRYT.

Figure 22 (left) shows the click counts for the KRYT METAR station for the control group and the experimental group. There is a higher count of METAR activations for the experimental group (N = 299) than the control group (N = 211). As shown by the posterior distribution (right), this difference is credible (mode = 0.352) as the value 0 is not included in the 95% HDI. Evidently, the state-change notification alerted participants to the updated METAR information, which resulted in a higher count of METAR clicks for the experimental group.

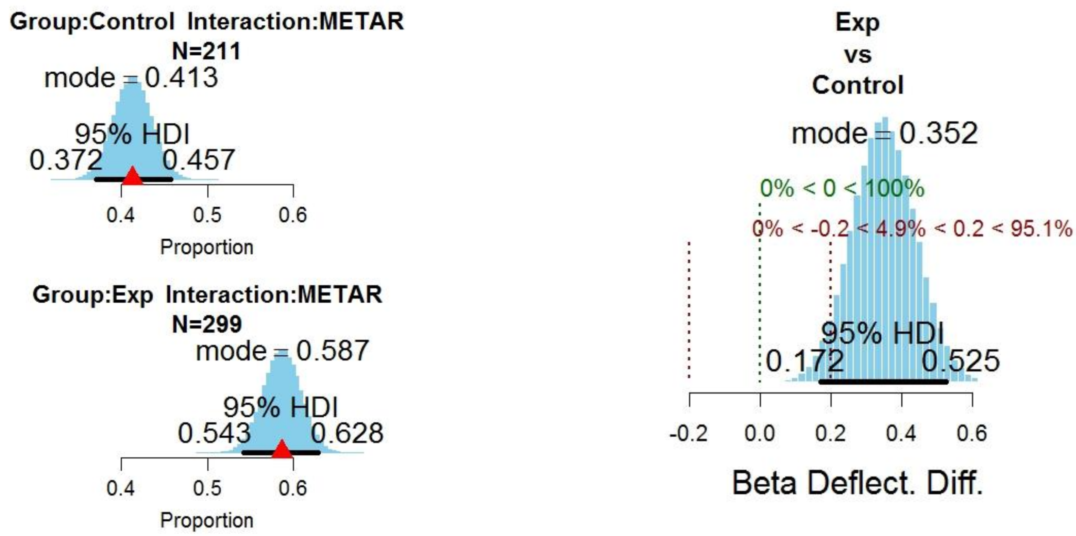



*Figure 22.* Posterior distributions (left) for counts and estimated cell proportions for KRSP METAR interactions and the posterior difference (right) between the experimental group and the control group.

We also assessed METAR interactions for all other stations symbols than the KRSP and the KRYT METARs. There was a higher count for the control group (N = 63) than the experimental group (N = 49), but the posterior mean difference (–0.248) was not credible as the value 0 was included in the 95% HDI (–0.637 to 0.116).

### 3.2.3 Cognitive Workload

We measured participants' prefrontal oxygenation at 2 Hz during the scenario flight. We then averaged the oxygenation values across all 16 channels and computed an average for each participant. For the analysis we used a Bayesian model (see Kruschke, 2015; p. 449) for a metric-predicted variable (i.e., oxygenation values) for two groups (experimental vs. control).

Figure 23 shows the average oxygenation change and variability for the experimental group and the control group. First, the control group has, on average, higher oxygenation values than the experimental group. Second, there is a trend in the oxygenation data where the oxygenation values increase as scenario time increases.

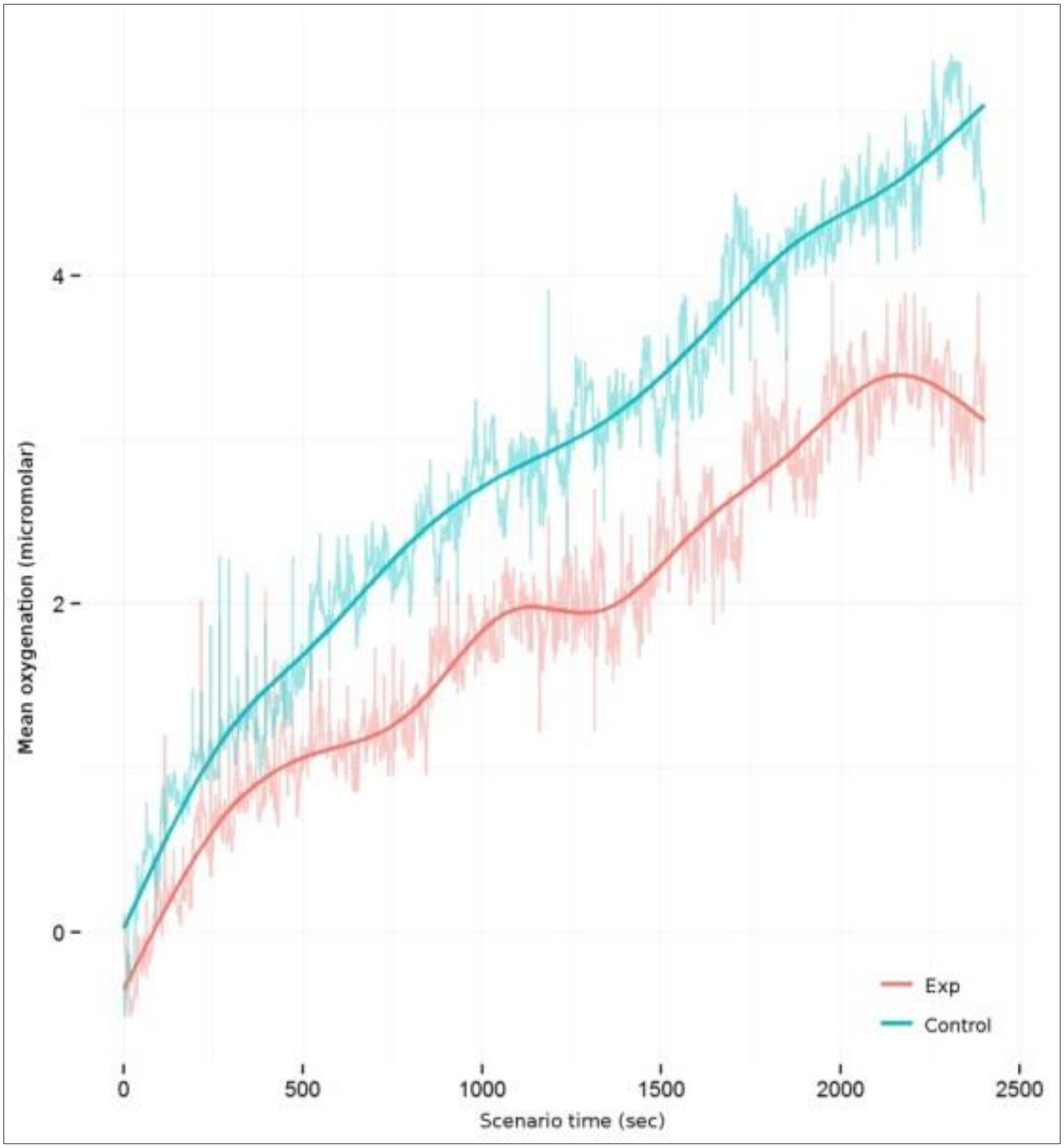



*Figure 23*. Mean oxygenation and variability for the experimental group and the control group as a function of scenario time.

Figure 24 shows the outcome of the analysis. On average, the control group had greater oxygenation changes (mode = 2.82) than the experimental group (mode = 1.9). The difference of the means (mode = –0.967) and the effect size (mode = –0.572) are both credible, with the value 0 outside the 95% HDIs.

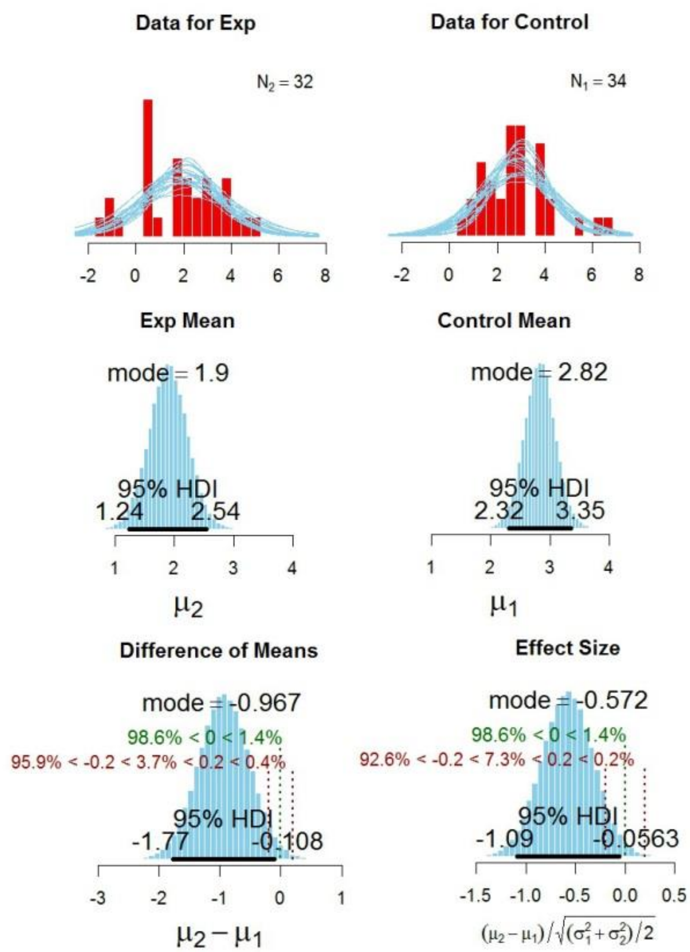



*Figure 24*. Mean fNIR oxygenation data (top) and posterior distributions for means (middle), difference of means (bottom left), and effect size (bottom right) for the comparison of oxygenation changes between the experimental group and the control group.

The outcome of the fNIR analysis is interesting in two ways. First, we know from scenario development that piloting gets more involved as participants approach the destination. At start-up, the weather conditions were VMC with only smaller cloud formations at altitude. As the flight progressed, participants had to avoid areas of Marginal Visual Meteorological Conditions (MVMC) while also staying clear of the prohibited area P-40. While navigating to the destination airport at lower altitudes, the participants had to stay clear of areas of IMC. Considering these factors, we would expect a higher cognitive engagement as the flight progressed, which was observed for both the experimental group and the control group.

The second interesting aspect is that the control group had credibly higher oxygenation than the experimental group. We attribute the reduced cognitive load in the experimental group to increased participant WSA. Because of the state-change notifications, participants were more attentive to information on the weather presentation, which enhanced planning and decision-making and reduced cognitive load.

### 3.2.4 Post-Scenario Questionnaire

All participants completed a 10-item rating-scale questionnaire (see Appendix C); an additional yes or no item plus an open-answer item was provided to report any discomfort with the fNIR sensor. These results are presented in Appendix E. For the analysis of the ratings, we used a model by Kruschke (2015, p. 682) for an *ordinal-predicted* variable (i.e., questionnaire ratings) comparing two groups. No credible differences between control-group and experimental-group pilots were seen in the frequency or ease of use, the effectiveness of weather information, the trust in the displayed information, or the reported mental workload.

### 3.3 Change-Detection of Weather Display Elements

The change-detection experiment was specifically designed to assess pilot sensitivity to changes in SUA area outlines, METAR changes, and precipitation changes on the Topological, VFR, and IFR background maps as displayed on the cockpit weather presentation. Previous research by Beck, Lohrenz, and Trafton (2010), using target detection on aeronautical digital charts, showed that reaction times increase as the amount of global clutter increases, particularly when the target was in a high local-clutter region. This highlights the importance of extending previous research (Ahlstrom & Suss, 2014) of weather symbol detection on Topological maps, to include detection of weather symbols on VFR and IFR background maps due to the increased symbol crowding and clutter. Figure 25 illustrates the precipitation, SUA outline, and METAR symbology on the Topological (left), VFR (middle) and IFR (right) background maps.

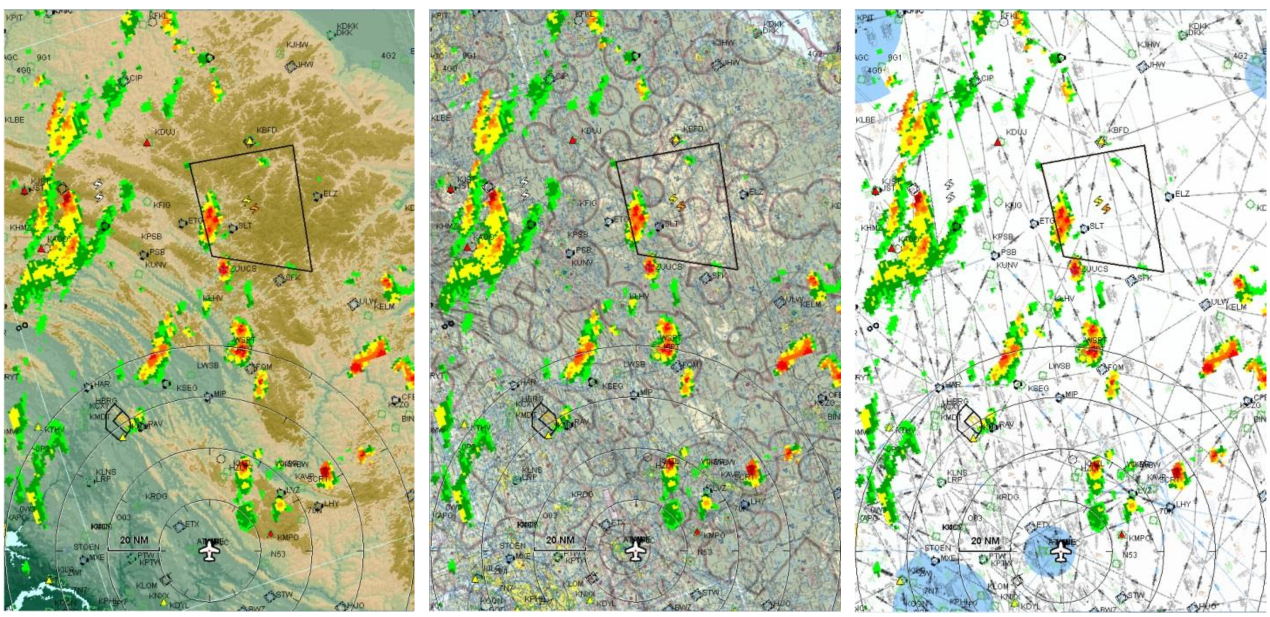



*Figure 25*. Illustration of the Topological (left), VFR (middle), and IFR (right) map backgrounds used during the simulation.

For the experiment, we created 36 unique trials by pairing specific weather images on the three map backgrounds (i.e., Topological, VFR, and IFR). During the experiment, each participant viewed and responded to each unique trial twice, yielding a total of 72 trials. In half of these trials there is a change between Image 1 and Image 2, with either an appearance of a weather element or a disappearance of a weather element. The trials were presented in random order.

We labeled all change trials as “signal” trials. We labeled the 50% of trials with no change as “noise” trials. The signal trials are described in Table 5. Figure 26 illustrates a signal trial for the disappearance of SUA area outlines (black lines). The SUA areas are visible in the left image (Image 1) but absent in the right image (Image 2).

**Table 5. Signal Trials for the Change-Detection Experiment**

| Weather element change | Trial type | Image 1 | Image 2 |
|---|---|---|---|
| METAR appearance (9 symbols) | Signal | Map w/o METAR | Map with METAR |
| METAR disappearance | Signal | Map with METAR | Map w/o METAR |
| SUA appearance (as shown in Figure 26) | Signal | Map w/o SUA outline | Map with SUA outline |
| SUA disappearance | Signal | Map with SUA outline | Map w/o SUA outline |
| Precipitation appearance | Signal | Map w/o precipitation | Map with precipitation |
| Precipitation disappearance | Signal | Map with precipitation | Map w/o precipitation |

*Note.* These trials were replicated for each weather presentation map background (i.e., Topological, VFR, and IFR). METAR = Meteorological Report; SUA = Special Use Airspace; VFR = Visual Flight Rules; IFR = Instrument Flight Rules.

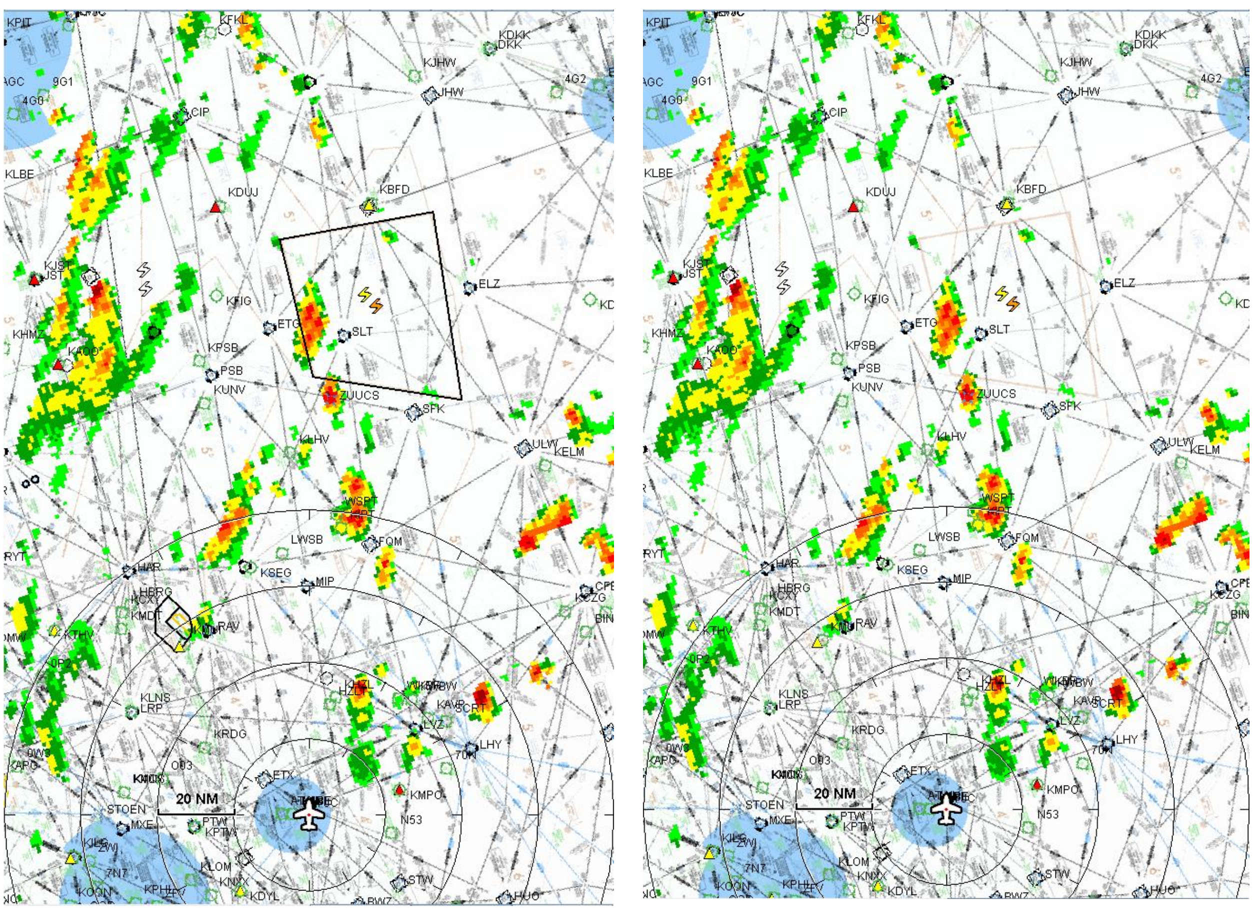



*Figure 26.* Illustration of the SUA area **signal** trial using the IFR map background—Image 1 (left) and Image 2 (right). The SUA areas disappear in the second image.

In the experiment, the noise trials were created by displaying the same signal image for both Image 1 and Image 2. Because we used YES and NO responses during the change-detection experiment, we labeled each response as

- a *hit* if the participant responded YES to a signal trial,
- a *false alarm* if the participant responded YES to a noise trial,
- a *miss* if the participant responded NO to a signal trial, and
- a *correct rejection* if the participant responded NO to a noise trial.

From the observed counts of hits, false alarms, misses, and correct rejections, we derived indices of discriminability ($d$) and bias ($c$) using a Bayesian Signal Detection Theory (SDT) model from Lee (2008). The discriminability index, $d$, measures how easily participants can distinguish signal trials (change) and noise trials (no change). The higher the $d$ value, the easier it is for participants to detect weather element changes—whereas a $d$ value of 0 corresponds to random guessing. The bias index, $c$, is a measure of the participant decision-making criterion. If a participant has a positive value of the bias index, the participant has a bias to respond NO—this will result in an increase in the number of correct rejections, but it will also result in an increase in the number of misses. If a participant has a negative bias index, the participant displays a bias towards answering YES—and this leads not only to an increase in the number of hits but also to an increase in the number of false alarms.

Even though the $d$ and $c$ indices are meaningful from a psychological performance standpoint, it can be difficult to grasp exactly what these indices imply for participant performance. For example, if a group of participants have a posterior average of $d = 1.8$ and $c = 0.8$, we can infer that the performance for this group is worse compared to another group that has a posterior average of $d = 2.8$ and $c = 0.1$. But how good is $d = 2.8$? And how bad is $d = 1.8$?

To help the reader with these questions, we introduce the concept of *ideal observers* (Olman & Kersten, 2004). An ideal observer in the current context is, as the name implies, an observer with ideal response characteristics. This implies that the observer has no response bias and always discriminates between signal and noise images with perfect accuracy. For each change-detection condition, we used the same Bayesian SDT approach to derive the $d$ and the $c$ indices for a group of ideal observers (using the same N and total number of signal and noise trials as was administered to the study participants). In each result graph, we indicate the perfect performance for the group of ideal observers so that readers can gauge the performance of the study participants. The analysis for each change-detection condition shows that the posterior $d$ and $c$ derived from participant performances. The indication for the ideal observers, therefore, shows the best performance possible had the study participants performed with zero bias and perfect discrimination.

In addition to analyzing discriminability and bias, we also analyzed the response time for each change-detection trial during the experiment. In general, well-designed symbols and weather elements that produce good legibility and salience against the background are easier to detect and require less time to discriminate than elements with less optimal stimulus and background characteristics (McDougall, de Bruijn, & Curry, 2000). For the response time analyses, we used the combined response times for each signal and noise trial for each display element and participant.

Figure 27 shows the result summary, and Figure 28 shows the outcome in terms of discriminability and bias for the METAR detection on the IFR, VFR, and Topological backgrounds.

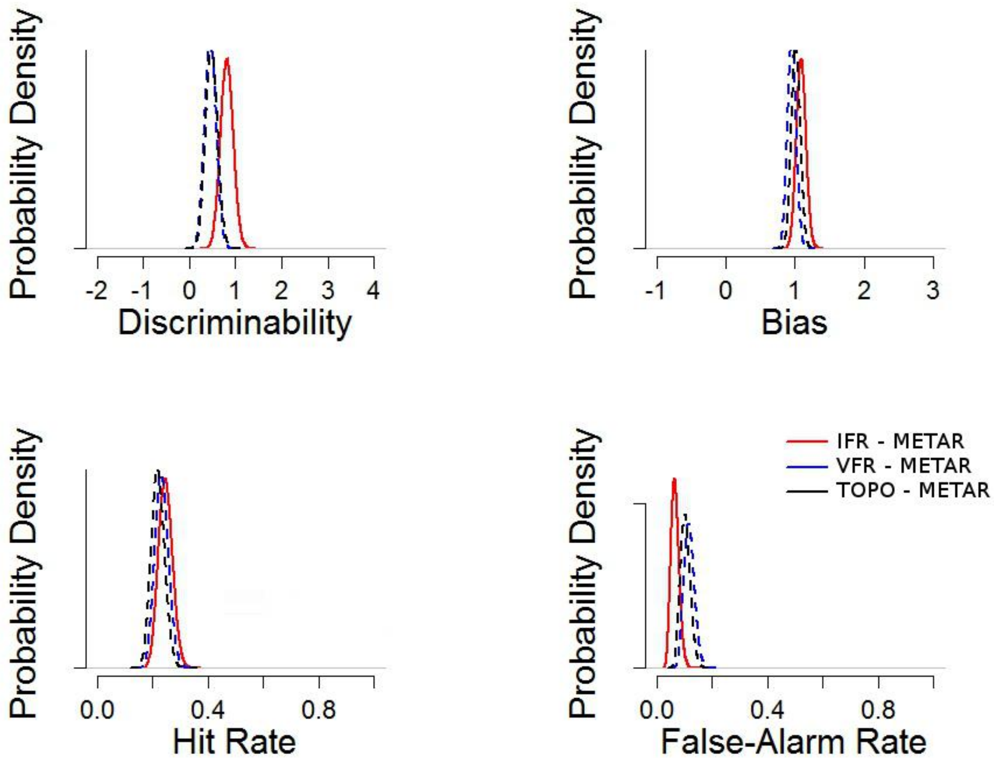



*Figure 27.* Analysis summary with discriminability (*d*), bias (*c*), hit rate, and false-alarm rate for the comparison of METAR changes on the IFR, VFR, and Topological backgrounds.

First, discriminability is very low, with a posterior mean of *d* = 0.818 for the IFR background, *d* = 0.459 for the VRF background, and *d* = 0.486 for the Topological background. On average, participants were more effective in discriminating METAR changes on the IFR map compared to the VFR map and the Topological map. Nevertheless, the data shows that participant performance in discriminating METAR symbols is very poor for all three backgrounds. If we compare participant performance to the group of ideal observers, we see that participant discriminability is at the opposite end of the performance spectrum.

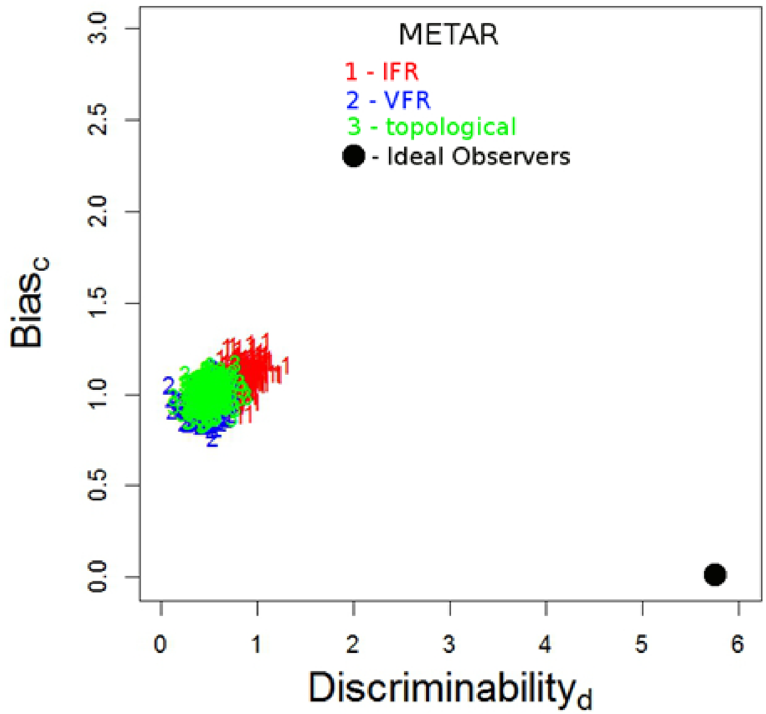



*Figure 28*. Discriminability (*d*) and bias (*c*) for the comparison of METAR changes on the IFR, VFR, and Topological backgrounds. The black dot indicates the mean posterior *d* and *c* for a group of Ideal Observers.

Figure 29 shows the posterior contrasts for the comparison in discriminability, *d*, of METAR symbols on the IFR, VFR, and Topological backgrounds.

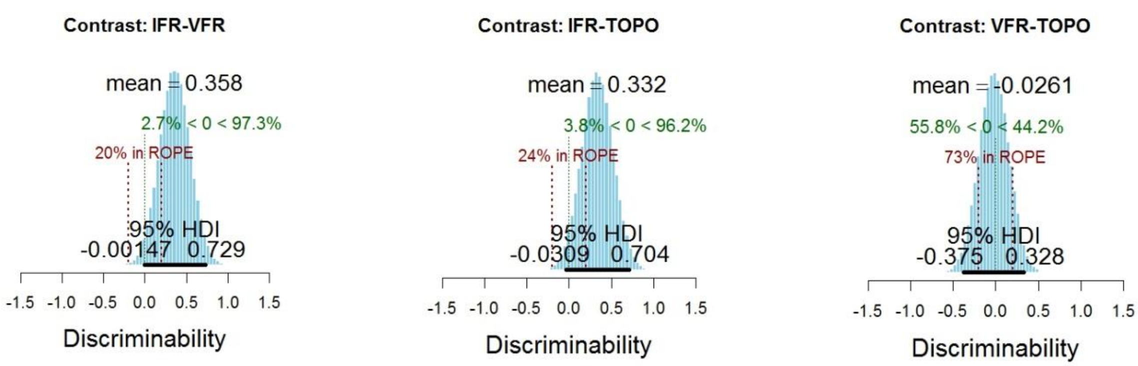



*Figure 29*. Posterior contrasts (differences) for the discriminability of METAR changes; IFR versus VFR (left), IFR versus Topological (middle), and VFR versus Topological (right).

Discriminability of METAR changes is higher on IFR map backgrounds than on VFR map backgrounds (mean difference = 0.358). Discriminability of METAR changes is also higher on IFR map backgrounds than on Topological map backgrounds (mean difference = 0.332). There is no difference in discriminability of METAR changes between VFR maps and Topological maps (mean difference = –0.0261). However, because the value 0 is included at the left end of the 95% HDIs for the IFR-VFR (HDI from –0.00147 to 0.729) and IFR-TOPO (HDI from –0.0309 to 0.704) contrasts, we cannot unequivocally say that the differences of means are credible. A difference of 0 is one of the possible outcomes, but with a very small probability.

The sample median response time for METAR trials on the IFR, VFR, and Topological map backgrounds were 1.732, 1.989, and 1.95 seconds, respectively. Because response time data always have skewed distributions, we performed a $\log_{10}$ transformation prior to the analysis. Posterior contrasts (see Figure 30) revealed credible differences between METAR discrimination on the IFR and Topological backgrounds (mean posterior difference = –0.0197), with longer response times for Topological background trials. There was also a credible difference in response times between IFR and VFR trials (deflection difference mean = –0.0198), with longer response times for METAR discrimination on VFR backgrounds. There was no difference in response times between VFR and Topological backgrounds.

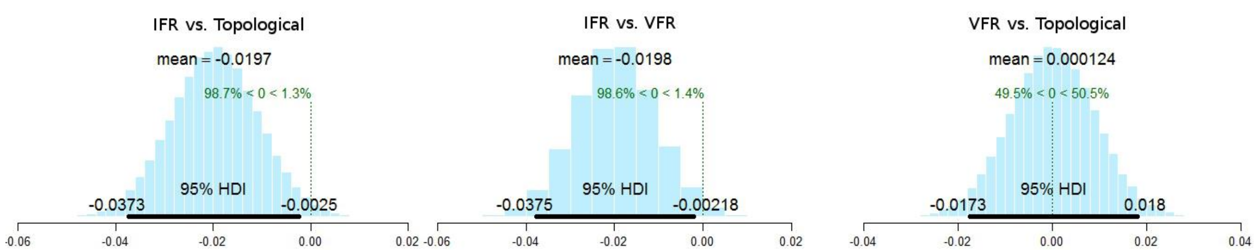



*Figure 30.* Posterior contrasts of deflection values for $\log_{10}$ transformed response times to METAR trials on IFR, VFR, and Topological background maps.

Figure 31 shows the analysis summary, and Figure 32 shows the discriminability and bias for the Precipitation detection on the IFR, VFR, and the Topological backgrounds. Contrary to the low hit rate for METAR detections, the hit rate for precipitation changes is very high. The participant bias is low, with a mean around 0 for all three precipitation conditions, mimicking the bias of the group of ideal observers. Participant discriminability is also very similar for all three map backgrounds, with a posterior mean of $d$ = 2.56 for the IFR background, $d$ = 2.44 for the VRF background, and $d$ = 2.29 for the Topological background. Although the discrimination performance is moderate for the group of participants, it is still much lower compared to the ideal observers. When analyzing the data, we found that none of the contrasts revealed credible differences in $d$ between the three map backgrounds.

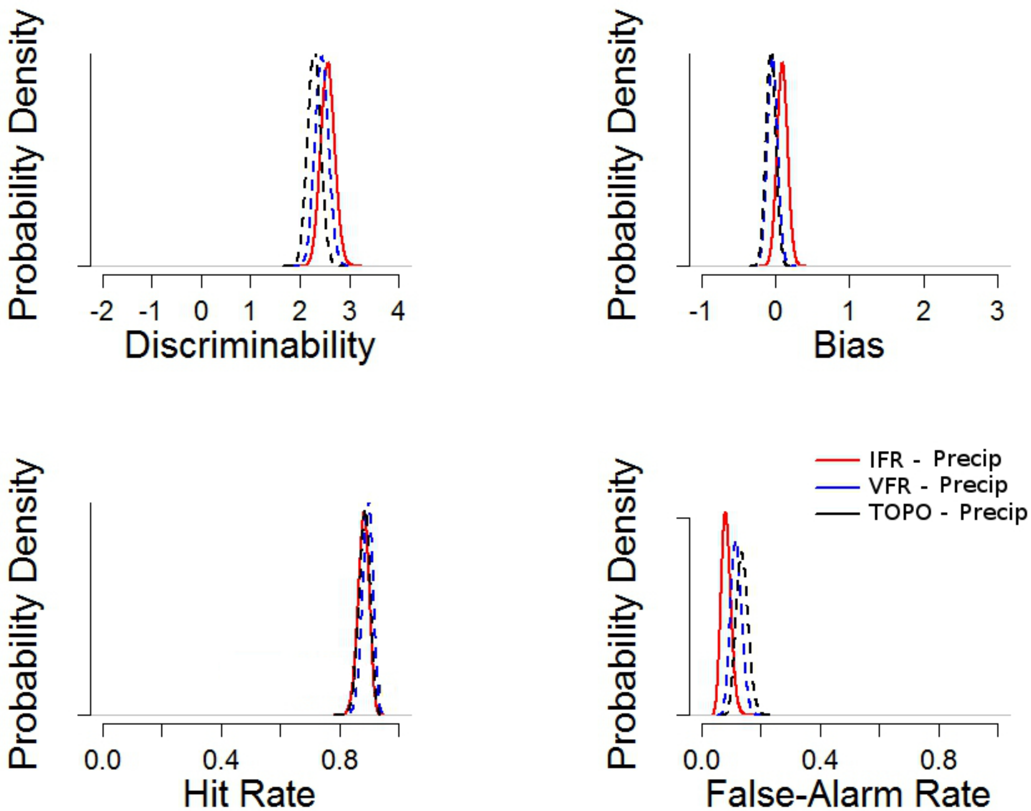



*Figure 31*. Analysis summary with discriminability (*d*), bias (*c*), hit rate, and false-alarm rate for the comparison of Precipitation changes on the IFR, VFR, and Topological backgrounds.

The sample median response time for precipitation trials on the IFR, VFR, and Topological map backgrounds were 1.653, 1.599, and 1.677 seconds, respectively. Posterior contrasts revealed a credible difference between the log transformed response times for the VFR and the Topological conditions with longer response times for the Topological trials (deflection mean = –0.021, 95% HDI extending from –0.0001 to –0.041 and excluding the value 0).

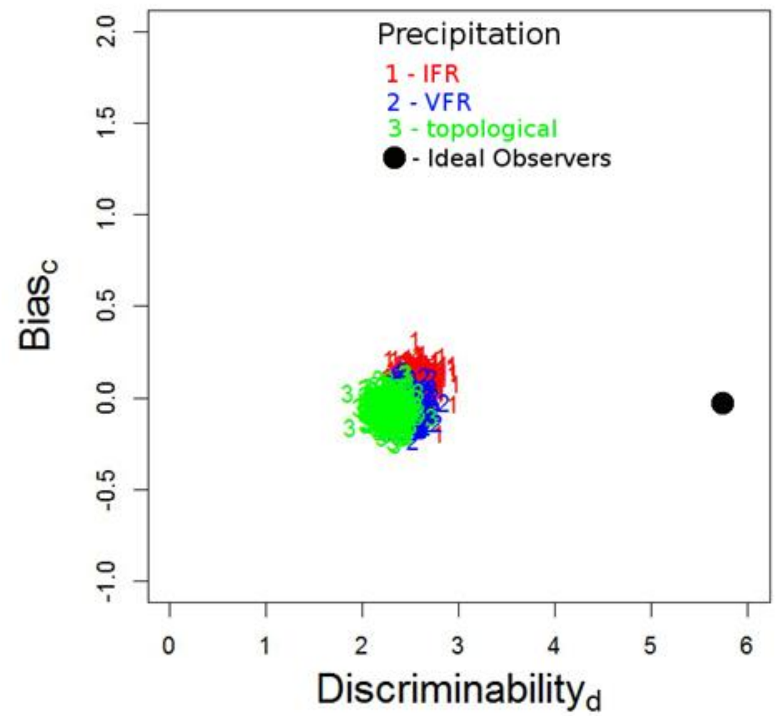



*Figure 32*. Discriminability (*d*) and bias (*c*) for the detection of Precipitation changes on the IFR, VFR, and Topological backgrounds. The black dot indicates the mean posterior *d* and *c* for a group of Ideal Observers.

Figure 33 shows the analysis summary, and Figure 34 shows the posterior contrasts for the comparison in discriminability of SUA symbols on the IFR, VFR, and Topological backgrounds.

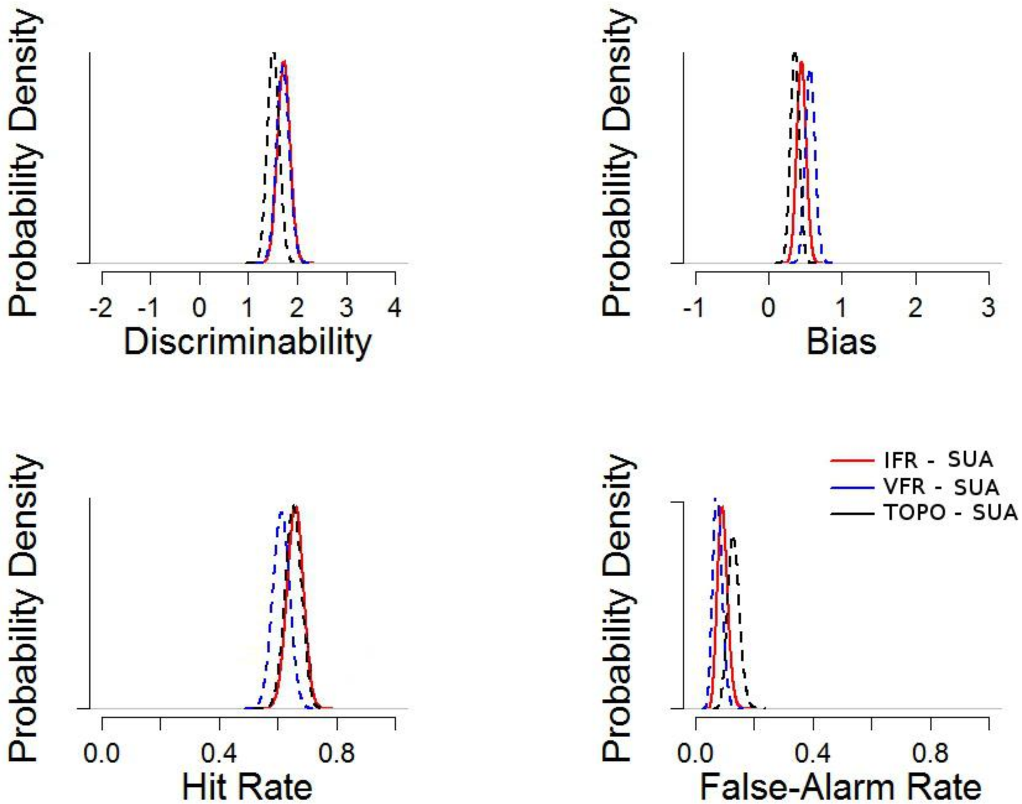



*Figure 33*. Analysis summary with discriminability (*d*), bias (*c*), hit rate, and false-alarm rate for the comparison of SUA changes on the IFR, VFR, and Topological backgrounds.

First, the average bias ranges from .03 to .05 and is in-between the average participant bias for the METAR and the precipitation data. Second, the discriminability is very similar across the three backgrounds, with a mean $d = 1.73$ for the IFR background, $d = 1.71$ for the VFR background, and $d = 1.51$ for the Topological background. Comparing the discriminability performance with the group of ideal observers, the participants are almost at the opposite end of the performance scale. An analysis on the participant data revealed no credible differences in *d* between the three map backgrounds.

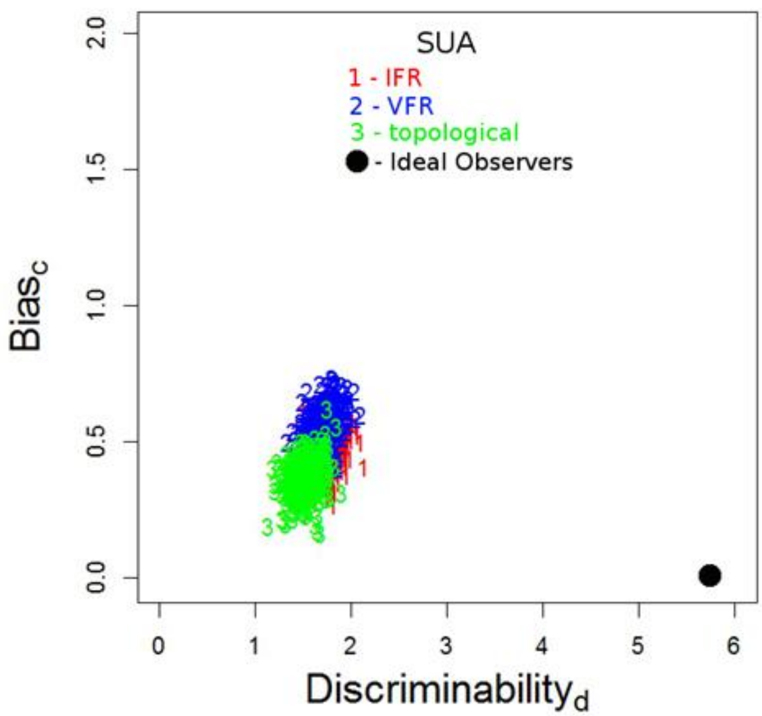



*Figure 34*. Discriminability (*d*) and bias (*c*) for the detection of SUA changes on the IFR, VFR, and Topological backgrounds. The black dot indicates the mean posterior *d* and *c* for a group of Ideal Observers.

The sample median response time for SUA trials on the IFR, VFR, and Topological map backgrounds were 1.825, 1.817, and 1.794 seconds, respectively. There were no credible differences between these response times.

To summarize, the results from the change-detection experiment revealed that discriminability is similar for SUA and Precipitation elements on the IFR, VFR, and Topological map backgrounds. Despite the increased complexity and clutter on the IFR and VFR maps, in general, there is no credible decrement in participant performance. One exception is the discriminability of METAR changes; the discriminability is higher on IFR map backgrounds than on VFR and Topological map backgrounds. Also, in addition to a higher METAR discriminability on IFR background maps, the discrimination response times are credibly shorter for METAR discrimination on IFR maps compared to VFR and Topological maps.

### 3.4 Summary of Study Findings

Ahlstrom and Suss (2014) investigated three unique weather presentation symbologies during a VFR simulator flight to assess pilots' sensitivity to METAR symbol changes. The results showed that pilots had great difficulty detecting METAR symbol changes for all three presentations. Ahlstrom and Suss (2014) attributed the low symbol detection performance to a well-known phenomenon, change blindness, which is particularly strong during multitasking situations such as single pilot operations.

We designed the study to support or refute our hypotheses ($H_1$ - $H_4$) about the use of weather state-change notifications (via tactile feedback) and whether they improve pilot change detection of weather symbols during flight. In this section, we outline the four hypotheses with study results and provide a summary (see Table 6).

**Table 6. Summary of Study Hypotheses and Outcomes**

| Hypothesis | Supported by study results | Not supported by study results |
|---|---|---|
| ***$H_1$***: Implementing a tactile state-change notification function to the presentation of selected weather information will result in earlier and more accurate pilot recognition of the weather-state change associated with the notification function. | √ | |
| ***$H_2$***: Earlier recognition of weather and weather-state changes will afford pilots more time to take appropriate action to avoid adverse weather. | | ✕ |
| ***$H_3$***: Earlier adverse weather avoidance decision-making will result in pilots maintaining a recommended distance from the weather event. | | ✕ |
| ***$H_4$***: Implementing tactile weather notification functions without degrading pilot performance on safety-related flight tasks, actions, and decisions. | √ | |

### ***$H_1$: State change notification can result in earlier and more accurate pilot recognition of weather-state changes.***

#### *Flight trajectory*

We assessed participants' general flight behavior—as they avoided clouds at altitude and avoided areas of reduced ceiling and visibility along the route—by analyzing participants' vertical and horizontal flight profiles. We found no credible differences in the vertical and horizontal flight profiles between the experimental and control groups. There were also no credible differences between groups in how they deviated from the pre-planned route or how closely they flew to the prohibited P-40 area, although there were two P-40 airspace violations in the experimental group.

#### *Communications and weather situation awareness*

Although we found no credible difference in flight profiles, participants in the experimental group (a) provided credibly more communications of weather data and maneuver/course change information, (b) provided a higher number of out-the-window weather reports, and (c) exhibited an increased interaction with the cockpit weather presentation. We conclude that the experimental groups' exposure to the state-change notifications for METAR changes during flight had the effect of prompting participants to pay closer attention to the weather presentation, thereby improving their WSA. This supports our hypothesis that weather state-change notifications result in earlier and more accurate participant recognition of weather-state changes, thereby improving WSA.

***$H_2$: Earlier recognition of weather-state changes can afford pilots more time to take appropriate action to avoid adverse weather.***

We did not find credible differences in participant decision-making to deviate due to encounters with hazardous precipitation or reduced visibility to support this hypothesis. However, there were more decisions to divert to an alternate airport due to weather in the experimental group (61% of participants) than in the control group (53% of participants). On average, the time of the announcement of the decision to divert occurred 3.6 minutes earlier in the control group than in the experimental group at an average of 30.5 min into the scenario.

***$H_3$: Earlier adverse weather avoidance decision-making can result in pilots maintaining a recommended distance from the weather event.***

Our analysis found no credible differences between the experimental group and the control group regarding the average distance-to-weather or the closest distance-to-weather. Both groups had an average scenario distance-to-weather (30 dBZ cells) of 20 nmi, and an average closest distance-to-weather of approximately 5 nmi. This implies that participants were not following current guidelines for weather avoidance (i.e., 20 statute miles)—they flew too close to hazardous weather cells—a result similar to what was found by Ahlstrom and Dworsky (2012). As a result of flying close to weather, participants reported Loss of VFR conditions as they entered smaller cloud formations or haze in the vicinity of storm cells. There were no credible difference between groups with regards to participant reports of VFR flight into IMC conditions, although there were more participants in the control group (N = 33) than participants in the experimental group (N = 27) who reported a Loss of VFR conditions.

***$H_4$: Weather notification functions can be implemented without degrading pilot performance on safety-related flight tasks, actions, and decisions.***

When analyzing the fNIR data, we found credibly higher oxygenation levels for the control group than for the experimental group, indicating that participants in the control group had higher cognitive load during flight. This supports the hypothesis that weather notifications can be implemented without degrading pilot performance. We attribute the reduced cognitive load in the experimental group to increased participant WSA. By receiving state-change notifications, participants were more attentive to weather information and could therefore plan and make decisions with less cognitive effort than the control group.

### 3.5 Flight Profiles

Our examination of flight trajectory data and communications helped us determine if there was an effect from weather application use on a pilot's WSA. In looking at vertical flight profiles we found no credible differences in altitude changes between the experimental group (portable weather application) and the control group (no weather information). However, when analyzing the horizontal flight profiles we found a credible difference in route deviation during a convective weather scenario (Scenario A). The experimental group had credibly larger deviations from the pre-planned route compared to the control group. The experimental group had access to information that was used to plan and to make decisions whether to stay on the route or to deviate from areas of hazardous weather. These results indicate a positive effect on participants' WSA from the use of the portable weather presentation.

### 3.6 Communications

An analysis of the captured transmissions related to providing weather information from METARs, TAFs, and information related to weather-state changes acquired from the portable application, showed that the experimental group provided credibly more communications of weather information than the control group. Assessing the number of deviations to alternate airports and the scenario time at which they occurred, we found that the experimental group made more decisions to divert and that their decisions to divert came earlier in the scenario. However, because of the low numbers, neither the number of decisions to divert nor the time at which the diversions occurred was credibly different between groups. Nevertheless, these outcomes support our hypothesis that participants had increased WSA when using the portable weather application.

### 3.7 Pilot Sensitivity to Weather Element Changes

A secondary goal of the study was to assess participants' sensitivity to weather symbol changes. Using a change-detection experiment, we assessed participants' discrimination performance of signal and noise trials using METAR symbols, precipitation areas, and SUA outline information. In general, discriminability performance was low in all conditions when compared to the performance of a group of ideal observers. For the discrimination of METAR symbols, participants were more effective in discriminating METAR changes on the IFR map background compared to the VFR and the Topological map backgrounds. We also found credible differences in how long it took participants to respond—with longer response times for METAR discrimination on Topological backgrounds compared to IFR backgrounds and with longer response times for METAR discrimination on VFR backgrounds compared to IFR backgrounds. We found no credible differences in participants' discrimination of precipitation on the IFR, VFR, and Topological backgrounds. However, there was a credible difference in response times for the discrimination of precipitation on the VFR and the Topological map backgrounds, with longer response times for the Topological map backgrounds. Finally, the discrimination of SUA symbols on the IFR, VFR, and Topological backgrounds was also low without any credible differences between backgrounds. Taken together, these results indicate a discrimination behavior that is far from optimal. One exception is the METAR changes on the IFR map background that provided an increased luminance contrast between the target and background, resulting in higher discrimination and shorter response times. Although there were no detrimental effects on participants' ability to use the weather presentation for single-pilot flights, we interpret these findings to indicate that work is still needed to optimize the symbology for cockpit weather presentations. All symbol and background combinations should provide optimal luminance contrast, thereby enhancing symbol discrimination and reducing the time needed to differentiate all elements in the presentation.

## 4. DISCUSSION

In this study, participants in the experimental group (who received weather-change notifications) showed greater WSA than participants in the control group (who did not receive weather-change notifications). Here, notifications were delivered in the form of a tactile stimulus: Participants wore a bracelet that vibrated when an important change occurred on the weather display. Previous work has investigated the effect of tactile cues on pilots' ability to detect changes during flight. Sklar and Sarter (1999) also used a vibrating bracelet to notify participants of unexpected transitions between modes of an automated flight system, and found that tactile cues improved detection performance without impairing other aspects of performance.

In spite of their increased WSA, the experimental group was unable (a) to maintain safer separation from weather, (b) to better judge when to divert from the intended destination, and (c) to be more effective in avoiding flying into IMC conditions than the control group (without notifications). There are many potential reasons why the increased WSA did not translate into improved pilot behavior. First, it is possible that the out-the-window view of weather weighs more heavily in pilots' decision-making than the electronically displayed weather data. This could be an especially important factor for users who lack experience with electronic displays, thereby reducing the user's trust in displayed weather information while increasing the user's trust in visual information sampled from the out-the-window view. Second, it is also possible that the addition of kinesthetic and vestibular cues, which are absent in a fixed-base simulator (perception of wind gusts and turbulence), may be more compelling and more influential on pilots' real-life behavior when flying in close proximity to storms. Third, of the 73 pilots who participated in the simulation, 42 pilots reported having had no additional training in weather interpretation beyond basic pilot training. Weather interpretation experience is crucial; pilots may need training on how to translate an increased WSA into enhanced flight decisions. Participants in the present study mastered the use of the weather application, but what seems to be missing is a clear understanding of how to translate weather information into enhanced flight decisions. Previous work has shown that training on the interpretation of weather cues is successful for influencing pilots to make earlier deviations when they encounter hazardous weather (Wiggins & O'Hare, 2003). Similar training may help translate improved WSA into improved weather avoidance behavior.

Currently, many pilots receive inflight weather updates from cockpit weather displays like certified installed display systems or use subscriptions to commercial weather products that can be viewed on portable devices or on cell phones (FAA, 2010). These products allow the user to display a plethora of weather data. But having access to all this data does not guarantee that pilots understand how to correctly interpret the potential effects of weather hazards on their flight and how this information should be used for enhanced flight behavior. In fact, Johnson, Wiegmann, and Wickens (2006) found that pilots flying with weather displays were six times more likely to penetrate clouds than pilots flying with traditional instruments. Although the authors link this outcome to visual scanning and attentional tunneling, it also constitutes an example of a poor usage of cockpit weather displays. We know from in-depth pilot interviews that many GA users of commercial weather products have little or no training before they use the weather products in flight. This is a potentially dangerous situation in which the weather presentations afford users a sense of knowing (i.e., "I know what's going on") but without a real understanding of how to translate the data into enhanced behavior. In many respects, the current simulation exemplifies this dilemma. The experimental group pilots had good WSA but were as likely as the control group pilots to follow their pre-planned route when alternatives such as deviating, turning around, or landing at an alternate airport would have been more appropriate. This pattern of behavior has previously been described as plan-continuation errors (Wiggins, Azar, Hawken, Loveday, & Newman, 2014).

Previous experience with modern electronic displays is an important factor that affects pilots' flying behavior. For example, Wright and O'Hare (2015) found consistently poorer performance for pilots using glass cockpit displays compared to pilots using traditional displays when pilots had no previous experience with glass cockpit displays. Subjectively, however, pilots had a clear preference for the glass cockpit display. This further highlights a training need assessment due to the divide between improved behavior and actual behavior. Experience with electronic weather displays is another factor that is of importance for training on weather interpretation and how to translate weather information into enhanced flight decisions. The participants recruited for this study were generally older than the average age of student (31.5 years), sport (54.7 years), recreational (47.8

years), and private (48.3 years) pilots as described by FAA statistics on the age of active pilots. Furthermore, there were only a total of 16 participants who had previous experience with electronic weather displays. We believe this to be an important factor that could reduce the trust in displayed weather information while increasing the trust in out-the-window information. When asked to rate how much they trusted the weather presentation to give correct information, both the experimental group (rating mode = 3.79) and the control group (rating mode = 4.61) gave relatively low ratings on the seven-point rating scale. The posterior mean ratings for both groups only amounts to an "average" trust in the weather presentation halfway between the anchors, ranging from 1 (no*t at all*) to 7 (v*ery much*). Based on the groups' lack of previous experience with electronic displays and lack of weather training, it underscores a need for training in both how to correctly interpret weather information and how to translate this information to enhance flight decisions. We believe that with training the electronic display may become just as influential on pilots' decisions as the out-the-window view. We also believe that such training is crucial because the use of cockpit weather applications have become widespread.

Similar conclusions with regards to pilots' understanding of weather information, its effect on aviation, and training needs were stated by Lanicci et al. (2012). In their weather case-study review, they recommend better education and training on weather hazards and the appropriate use of this information during flight. Wiggins et al. (2014) have proposed a psychometric instrument that can uncover pilots that are at risk for making inaccurate weather-related decisions. The researchers also suggest that the method could be adapted for training on weather display interpretation. Similarly, Roberts, Lanicci, and Blickensderfer (2011) proposed a GA training module for the use of NEXRAD-based weather products. They reported preliminary results indicating that it was possible to achieve substantial results in educating and training pilots on the proper interpretation and the proper use of data-linked weather products.

## 5. CONCLUSION AND RECOMMENDATIONS

We found that weather state-change notifications increase pilots' WSA while decreasing their cognitive workload. However, these improvements did not translate to enhancements in flying behavior. Participants who received notifications and participants who did not receive notifications exhibited similar flying behavior. We believe this outcome is due to factors related to experience with electronic weather displays and the ability to translate weather information into more appropriate flight decisions. Finally, our change-detection experiment revealed that pilot discrimination performance was low for changes to METAR symbols, precipitation areas, and SUA outline information when compared to the performance of a simulated group of ideal observers. There were no detrimental effects on participants' ability to use the weather presentation for single-pilot flights, but we interpret these findings to indicate that work is still needed to optimize the symbology for cockpit weather presentations.

Based on the study outcome, there are four recommendations that need to be addressed by future research.

1. Assessment of the effect of pilot training to improve user trust in weather presentations.
2. Assessment of the effect of pilot training on how to interpret weather information on modern electronic displays.
3. Assessment of the potential effect from pilot training on how to translate weather information into improved flight decisions.

4. Research should provide weather presentations with optimal luminance contrast between weather elements and the backgrounds, thereby enhancing symbol discrimination and reducing the time needed to differentiate all elements in the presentation.

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## Acronyms

| | |
|---|---|
| AIRMET | Airmen's Meteorological Information |
| FAA | Federal Aviation Administration |
| FIS-B | Flight Information Services-Broadcast |
| fNIR | Functional Near-Infrared |
| GA | General Aviation |
| HDI | High Density Interval |
| IFR | Instrument Flight Rules |
| IMC | Instrument Meteorological Conditions |
| LCD | Liquid Crystal Display |
| MCMC | Markov Chain Monte Carlo |
| METAR | Meteorological Report |
| MVMC | Marginal Visual Meteorological Conditions |
| NEXRAD | Next-Generation Radar |
| NOTAM | Notice to Airmen |
| PIREP | Pilot Report |
| ROPE | Region of Practical Equivalence |
| SDT | Signal Detection Theory |
| SES | Stimulus Experiment System |
| SIGMET | Significant Meteorological Advisory |
| SME | Subject Matter Expert |
| SUA | Special Use Airspace |
| TAF | Terminal Area Forecast |
| TOPO | Topological Map |
| VFR | Visual Flight Rules |
| VMC | Visual Meteorological Conditions |
| VOR | Omnidirectional Radio Range |
| WMA | Windows Media Audio |
| WSA | Weather Situation Awareness |
| WTIC | Weather Technology in the Cockpit |

Appendix A: Informed Consent Form

## Informed Consent Statement

I, _______________________________, understand that this pilot study, entitled "Weather Technology in the Cockpit" is sponsored by the Federal Aviation Administration (FAA) and is being directed by Ulf Ahlstrom.

**Nature and Purpose:**

I volunteered as a participant in this study that encompasses two cockpit simulation flights and two symbol detection experiments. The primary purpose of the symbol detection experiments and the cockpit simulations are to improve General Aviation (GA) weather presentations for the cockpit. During the experiments, participants will evaluate sets of static images displayed on a computer monitor. During the simulation, participants will fly a single-engine GA simulator during Visual Flight Rules (VFR) conditions while avoiding encounters with hazardous weather.

**Research Procedures:**

Eighty GA pilots will participate as volunteers during a half-day (4 hours) that covers two simulation flights and two experiments. The participants will be engaged from 8:00 AM to 12:00 PM (or from 12:00 PM to 16:00 PM) with short rest breaks. All the participants will conduct the simulator flights before performing the experiments.

The first part of the session will encompass a briefing to review project objectives and participant rights and responsibilities. This briefing will also include initial familiarization training on the cockpit simulator, weather presentations, and the fitting of a head-mounted, Functional Near-Infrared Spectroscopy (fNIR) sensor used to measure cognitive workload. The participant will first complete a practice flight scenario. After the practice scenario, the participant will fly a designated route during a simulator flight (approximate duration: 40 minutes). During the simulator flight, an automated data-collection system will record cockpit system operations and generate a set of standard cockpit simulation measures including communications.

After the simulation flight, the participants will complete a questionnaire to report their overall workload, situation awareness, and provide an assessment of the cockpit system and test conditions. Additionally, participants will complete a brief biographical background questionnaire covering their flight and weather display experience.

After completing the questionnaires, participant will be briefed on the image detection experiment and thereafter conduct a training session. After the training session participants will complete the experimental task, which is divided into blocks. During these blocks, an automated data collection system records each participant response.

**Anonymity and Confidentiality:**

The information that I provide as a participant is strictly confidential and I shall remain anonymous. I understand that no Personally Identifiable Information [PII] will be disclosed or released, except as may be required by statute. I understand that situations when PII may be disclosed are discussed in detail in FAA Order 1280.1B "Protecting Personally Identifiable Information [PII]."

**Benefits:**

I understand that the only benefit to me is that I will be able to provide the researchers with valuable feedback and insight into weather presentation symbology. My data will help the FAA to establish human factors guidelines for weather displays and assess if there is a need to standardize the symbology for enhanced weather information.

**Participant Responsibilities:**

I am aware that to participate in this study I must be a GA pilot. I am also aware that I am not allowed to participate if I have a personal and/or familial history of epilepsy.

I will (a) fly the designated route in the cockpit simulations, (b) perform the experiments, and (c) answer questions asked during the study to the best of my abilities. I will not discuss the content of the part-task or the cockpit simulation with other potential participants until the study is completed.

**Participant Assurances:**

I understand that my participation in this study is voluntary, and I can withdraw at any time without penalty. I also understand that the researchers in this study may terminate my participation if they believe this to be in my best interest. I understand that if new findings develop during the course of this research that may relate to my decision to continue participation, I will be informed. I have not given up any of my legal rights or released any individual or institution from liability for negligence.

The research team has adequately answered all the questions I have asked about this study, my participation, and the procedures involved. I understand that Ulf Ahlstrom or another member of the research team will be available to answer any questions concerning procedures throughout this study. If I have questions about this study or need to report any adverse effects from the research procedures, I will contact Ulf Ahlstrom at (609) 485-8642.

**Discomfort and Risks:**

A fNIR sensor, consisting of a silicon pad containing small light-emitting diodes (LEDs) and light detectors, will be placed over the participant's forehead with a headband. Low power light will be shone onto the forehead area during the simulator flight, and changes in the amount of light that returns to the light detectors will be used to calculate changes in the concentrations of oxygenated and deoxygenated hemoglobin in the blood. The risk associated with using the fNIR sensor is less than the risk associated with spending an equivalent amount of time in the United States sunlight without wearing a hat. If the fNIR sensor causes discomfort, please alert the experimenter immediately.

In the part-task experiment, the screen may flicker back-and-forth between two images, at the rate of several times per second. For healthy individuals, there are no reported adverse effects of this common presentation technique. However, such flickering could cause seizures in epileptics. If you experience any discomfort due to the presentation of the images, please alert the experimenter immediately.

I agree to immediately report any injury or suspected adverse effect to Ulf Ahlstrom at (609) 485-8642.

**Signature Lines:**

I have read this informed consent form. I understand its contents, and I freely consent to participate in this study under the conditions described. I understand that I may request a copy of this form.

Research Participant:_________________________________________ Date:__________

Investigator:_________________________________________________ Date:__________

Witness:_____________________________________________________ Date:__________

Appendix B: Biographical Questionnaire

**Participant #** ___________ **Date** ___________

**Biographical Questionnaire**

Appendix A. This questionnaire is designed to obtain information about your background and experience as a pilot. Researchers will only use this information to describe the participants in this study as a group. Your identity will remain anonymous.

Demographic Information and Experience

| | |
|---|---|
| 1. What pilot certificate and ratings do you hold? (circle as many as apply) | Private Commercial ATP Glider<br>SEL SEA MEL<br>Airship Instrument CFI CFII<br>MEI Helicopter A&P IA |

| | |
|---|---|
| 2. What is your age? | _____ Years |
| 3. Approximately, what is your total time? | _____ Hours |
| 4. Approximately how many actual instrument hours do you have? | _____ Hours |
| 5. Approximately how many instrument hours have you logged in the last 6 months (simulated and actual)? | _____ Hours |

1. List all (if any) in-flight weather presentation systems you have used during a flight to make actual weather judgments (not including onboard radar or Stormscope).

___________________________________________

___________________________________________

2. Have you had any training in weather interpretation other than basic pilot training (for example, courses in meteorology)? If so, to what extent?

___________________________________________

___________________________________________

3. How often *do you provide/did you provide* pilot reports (PIREPs) during actual GA flights?

___________________________________________

___________________________________________

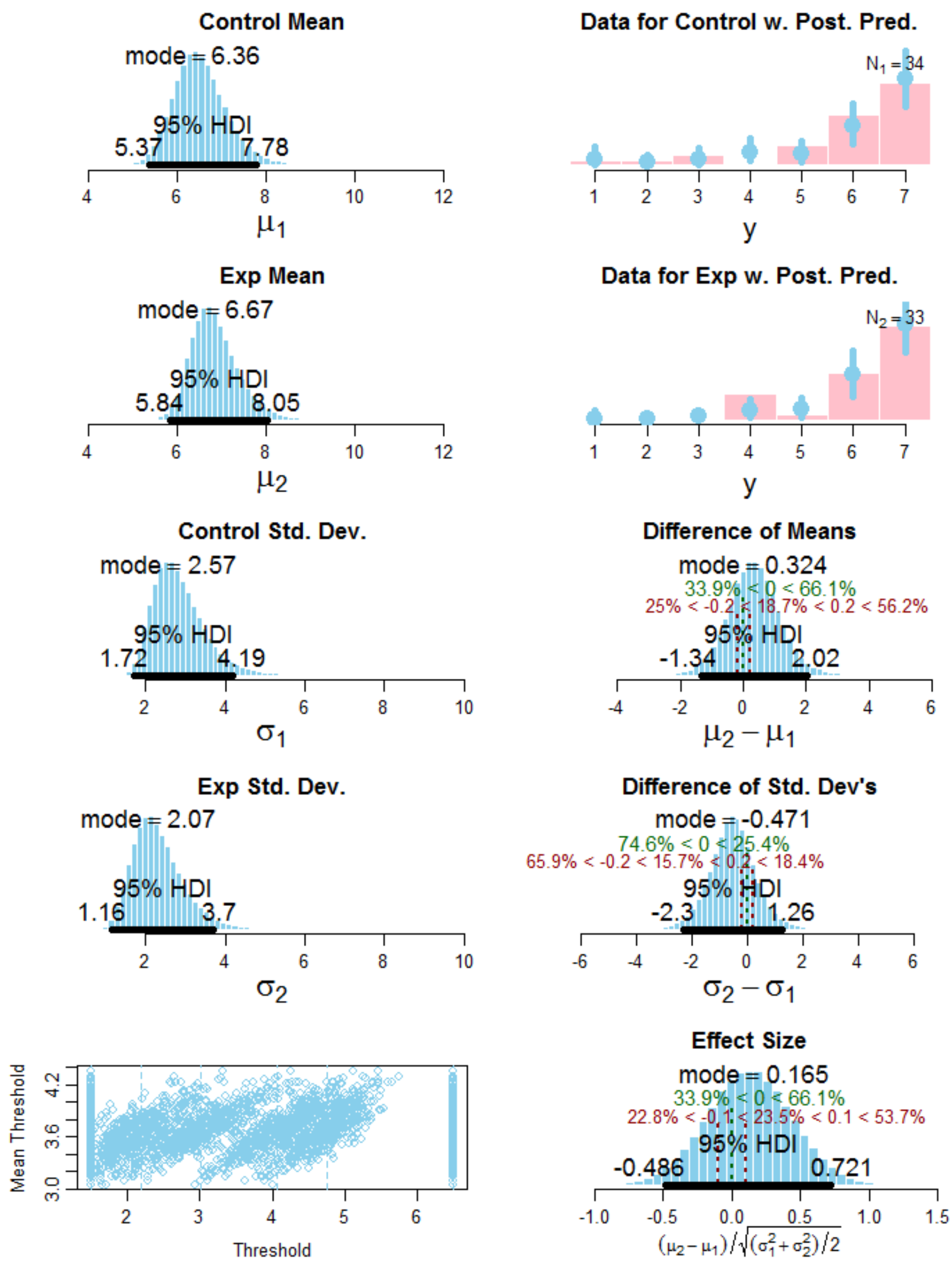
*Thank you very much for participating in our study, we appreciate your help.*

# Appendix C: Post-Scenario Questionnaire

# Post-Scenario Questionnaire with Analysis

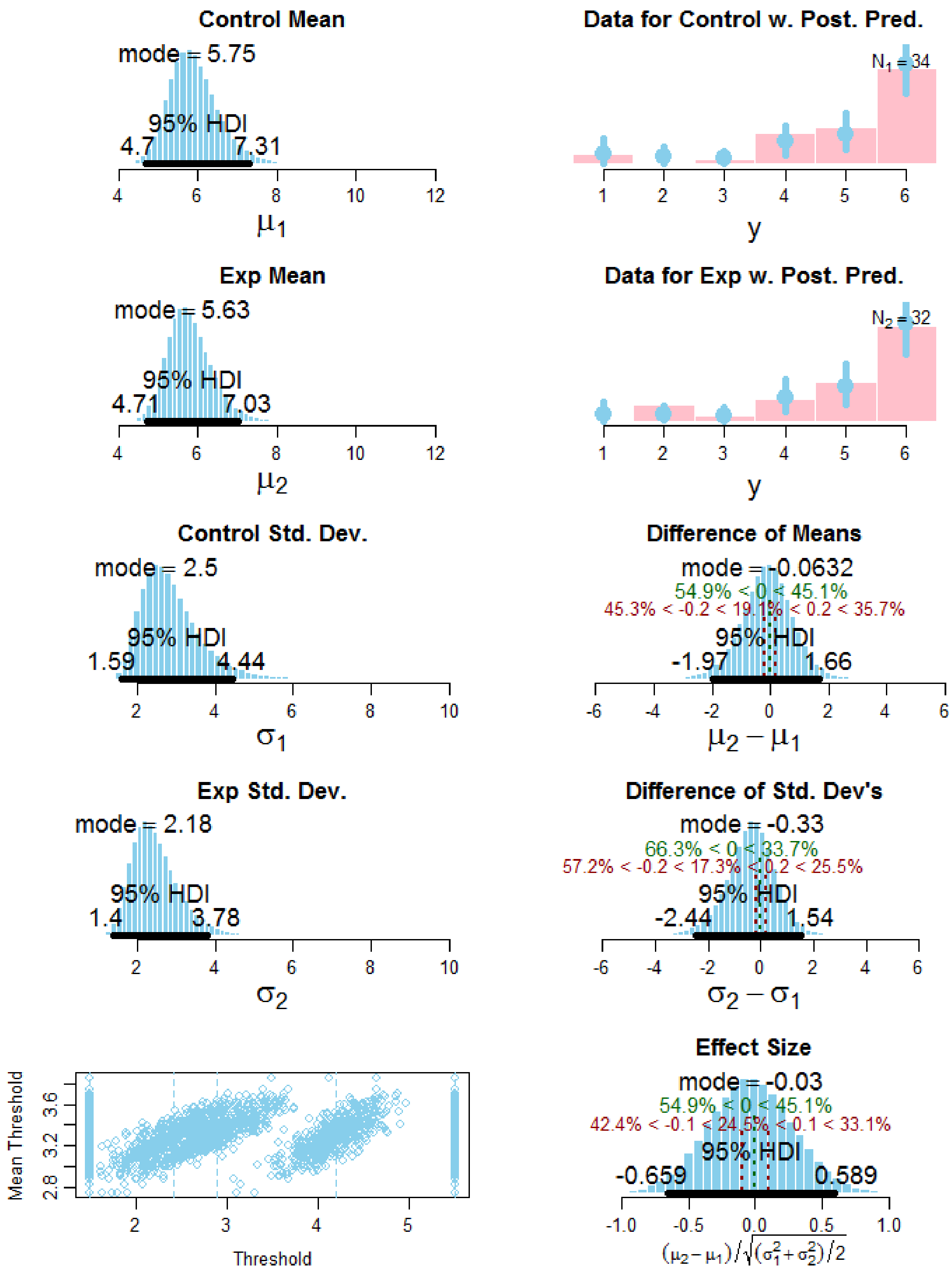
1. How often did you scan the weather presentation for weather changes?

| Never | | | | | | Very Often |
|---|---|---|---|---|---|---|
| **1** | 2 | 3 | 4 | 5 | 6 | **7** |



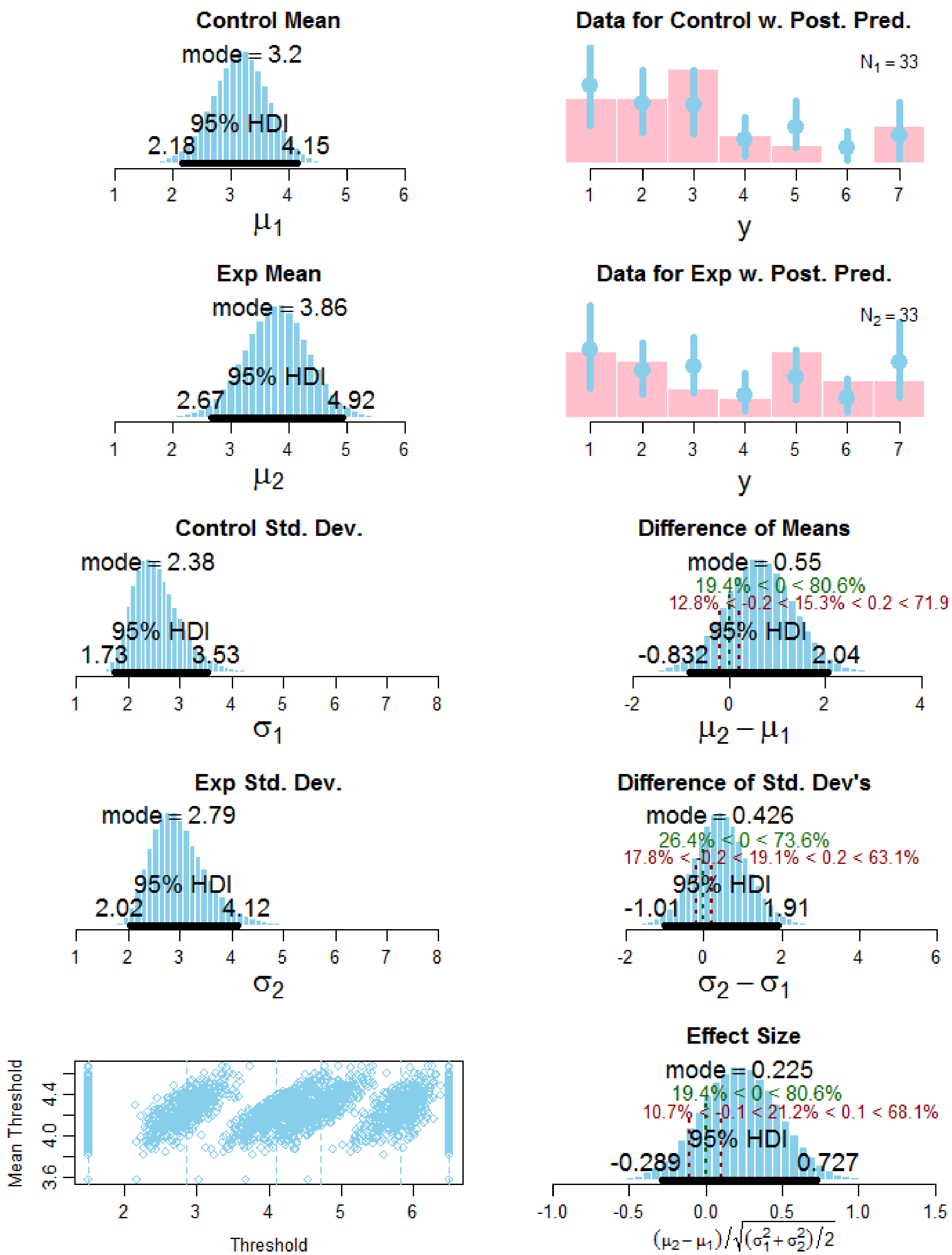
2. To what degree did the weather information affect your decision to deviate from your pre-planned course?

| **None** | | | | | | **Very Much** |
|---|---|---|---|---|---|---|
| **1** | 2 | 3 | 4 | 5 | 6 | **7** |



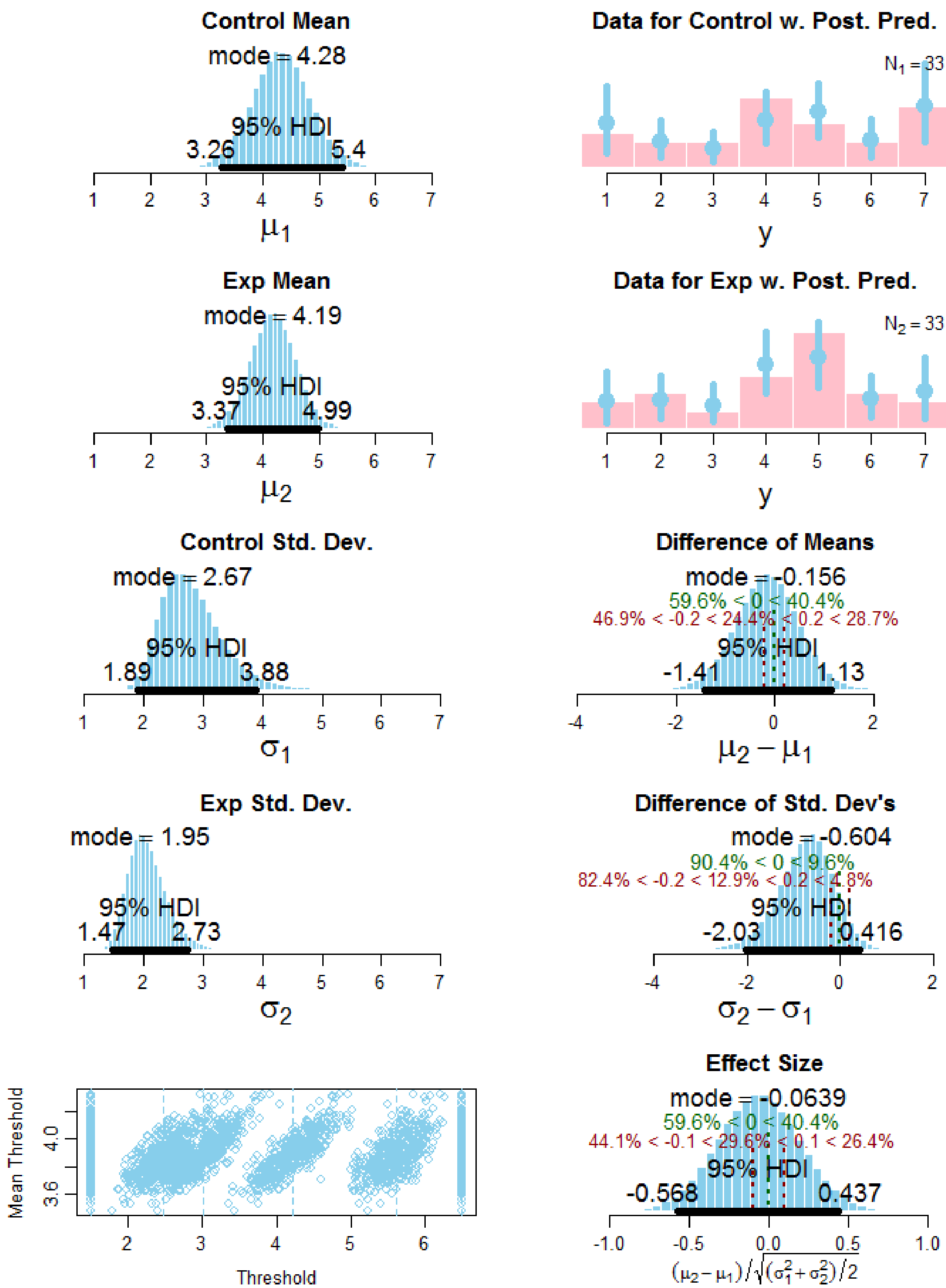
3. How easy was it to determine when a METAR symbol changed colors from VFR to IFR?

| Very Hard | | | | | | Very Easy |
|---|---|---|---|---|---|---|
| 1 | 2 | 3 | 4 | 5 | 6 | 7 |



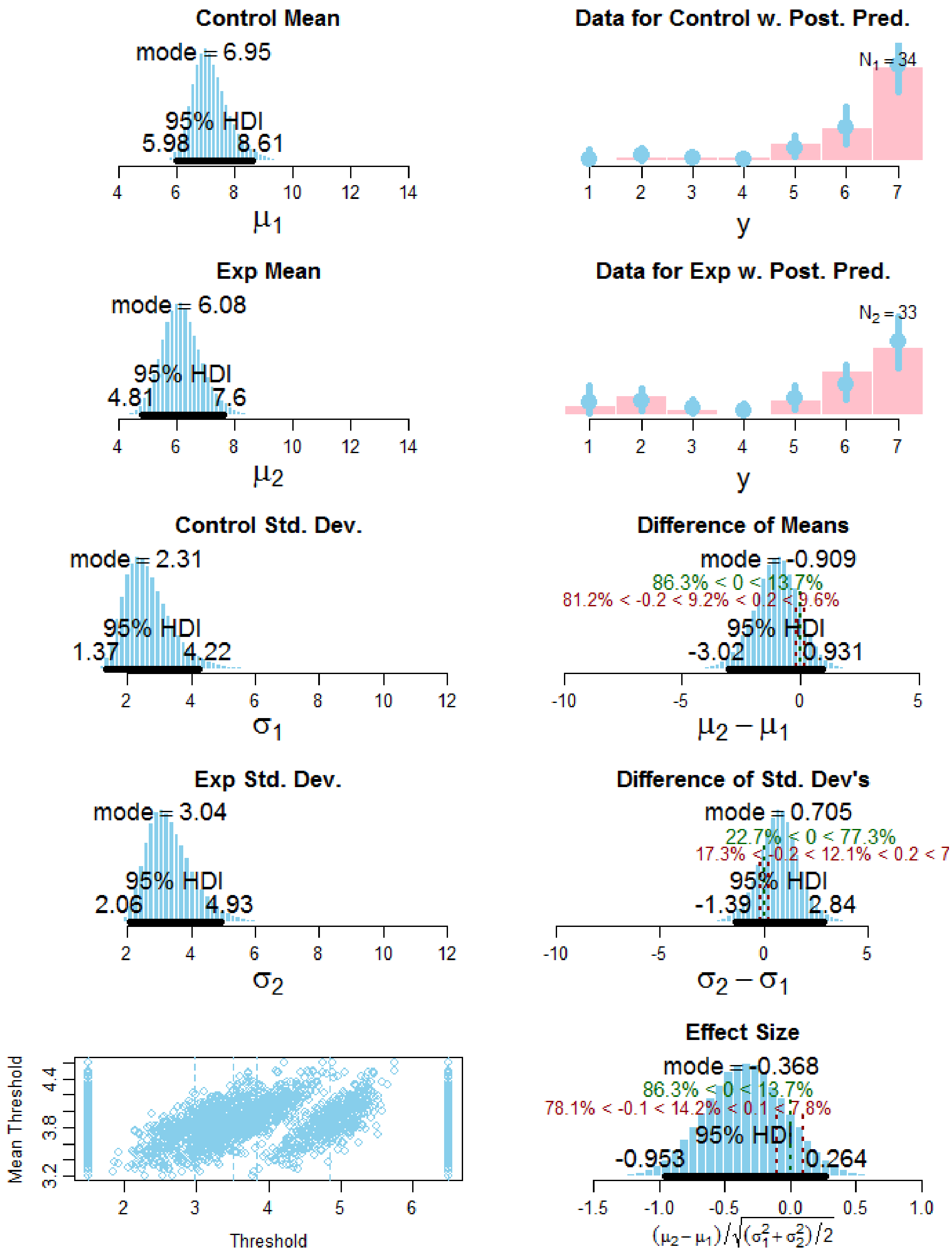
4. How useful was the METAR text information?

| Very Useful | | | | | | Not Useful at All |
|---|---|---|---|---|---|---|
| 1 | 2 | 3 | 4 | 5 | 6 | 7 |



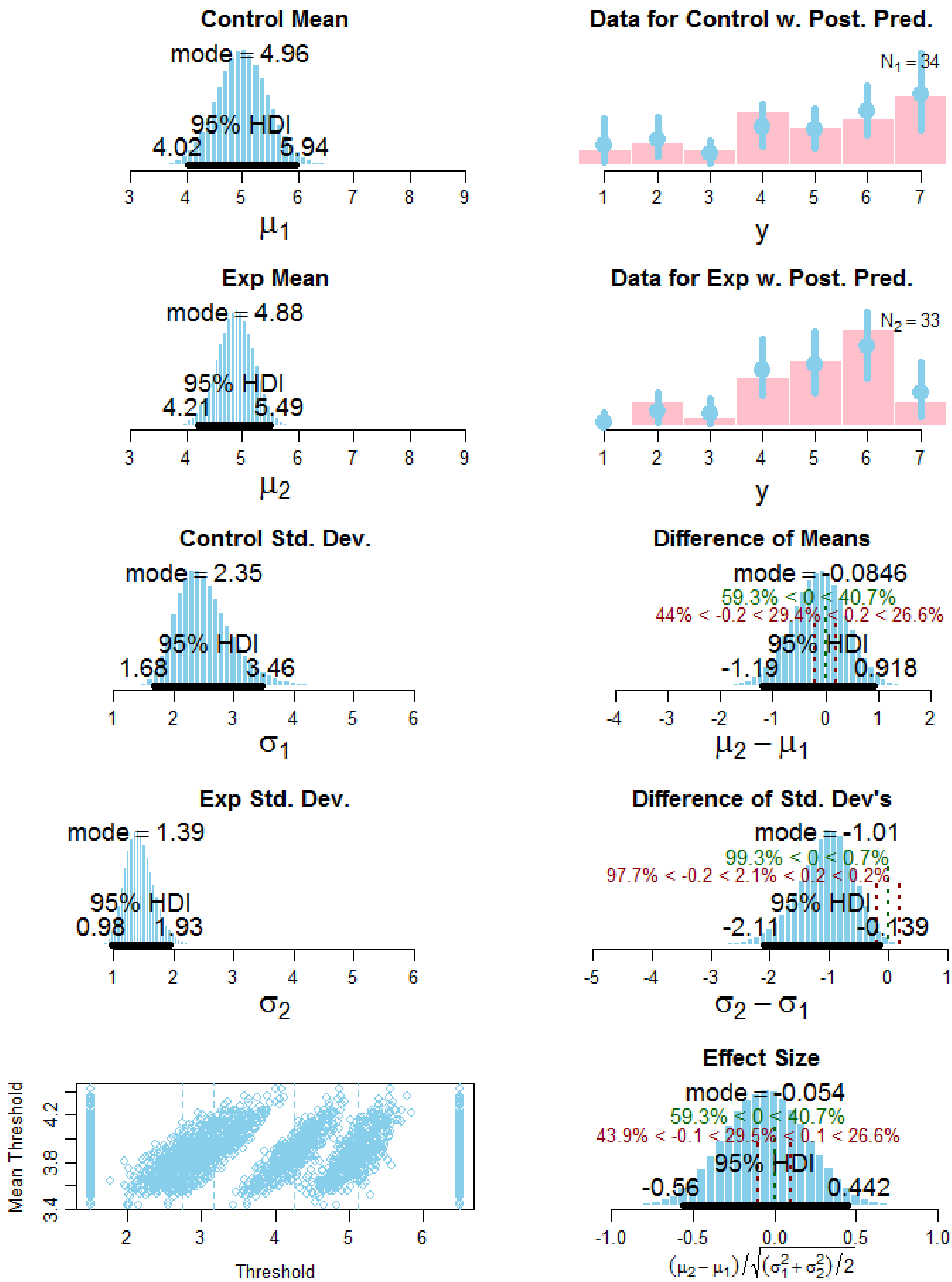
5. How easy was it to determine the location of severe precipitation areas?

| Very Hard | | | | | | Very Easy |
|---|---|---|---|---|---|---|
| 1 | 2 | 3 | 4 | 5 | 6 | 7 |



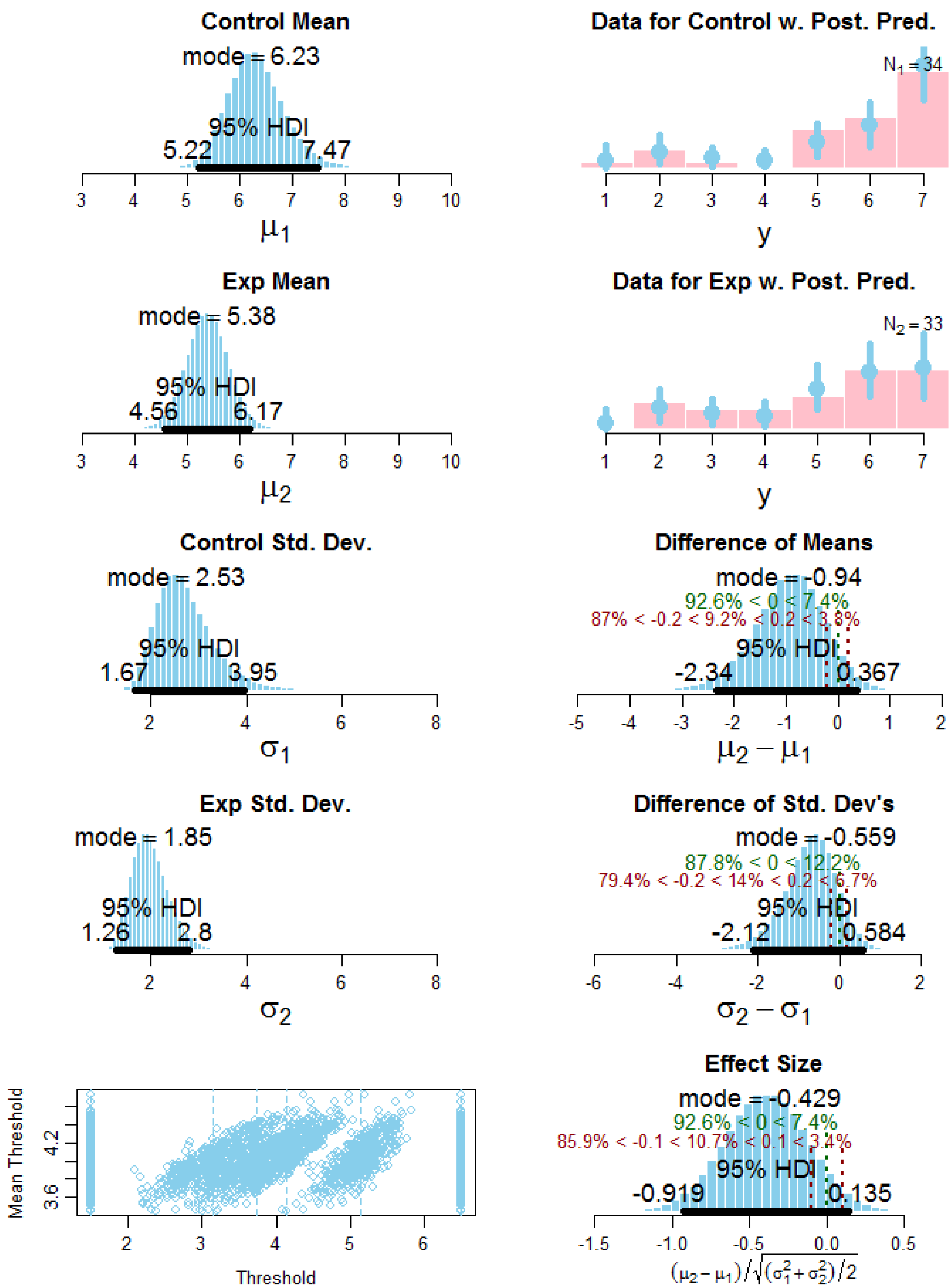
6. How easy was it to determine when precipitation areas changed location or intensity?

| Very Hard | | | | | | Very Easy |
|---|---|---|---|---|---|---|
| 1 | 2 | 3 | 4 | 5 | 6 | 7 |



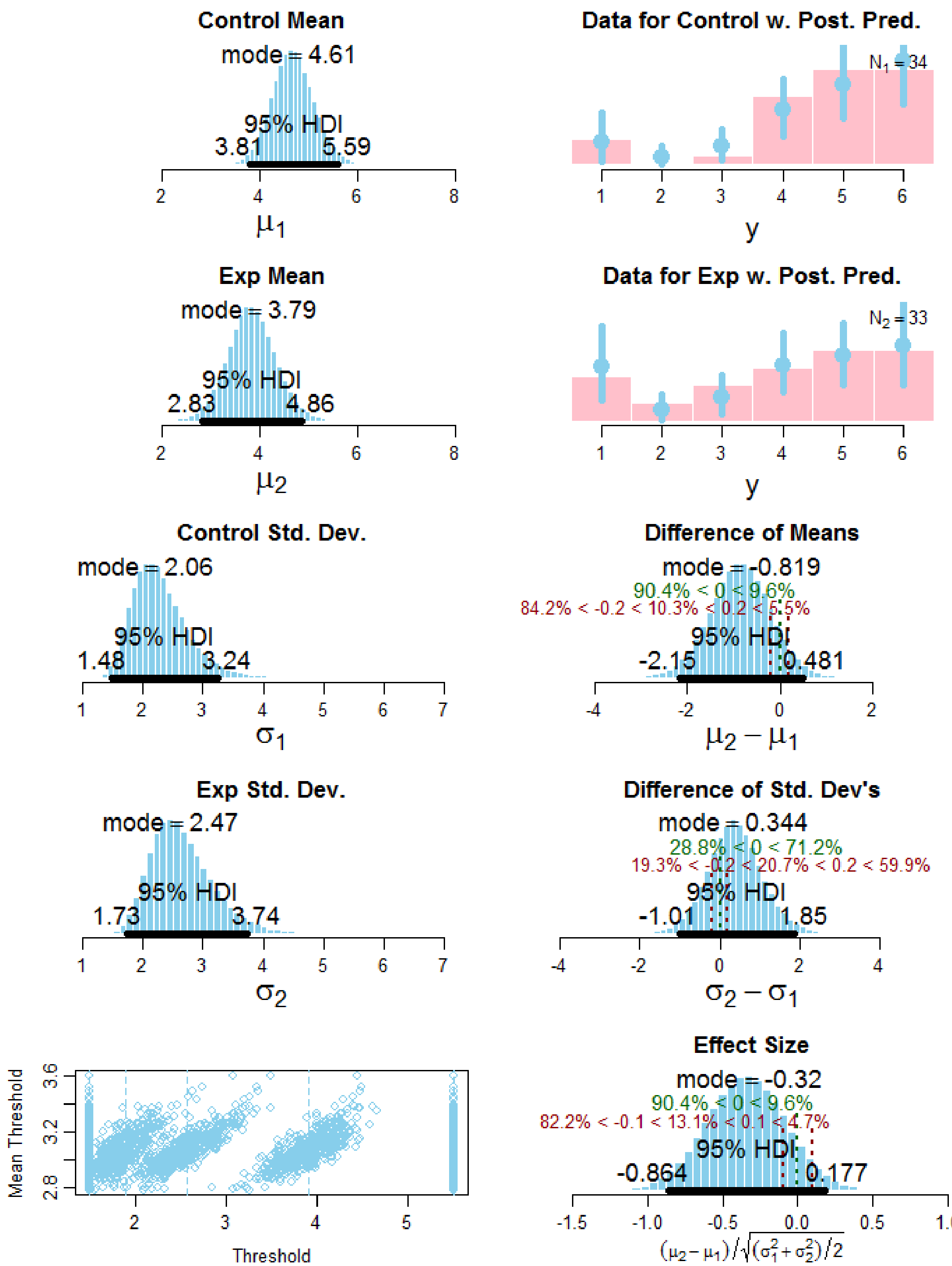
7. How much did the weather presentation reduce your workload associated with keeping away from hazardous weather areas?

| None | | | | | | Very Much |
|---|---|---|---|---|---|---|
| 1 | 2 | 3 | 4 | 5 | 6 | 7 |



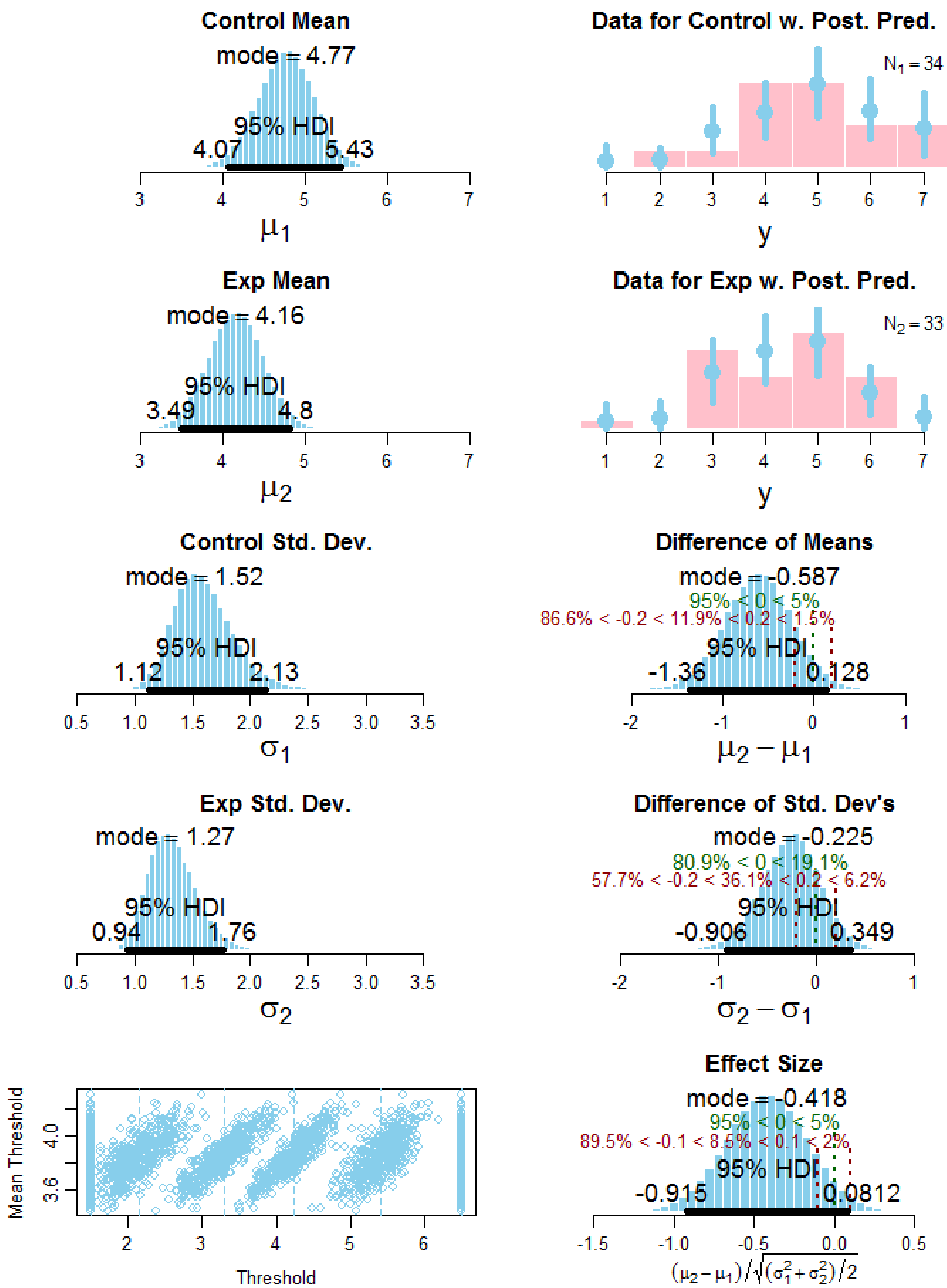
8. How much did you trust the weather presentation to give you correct information?

| Not At All | | | | | | Very Much |
|---|---|---|---|---|---|---|
| 1 | 2 | 3 | 4 | 5 | 6 | 7 |



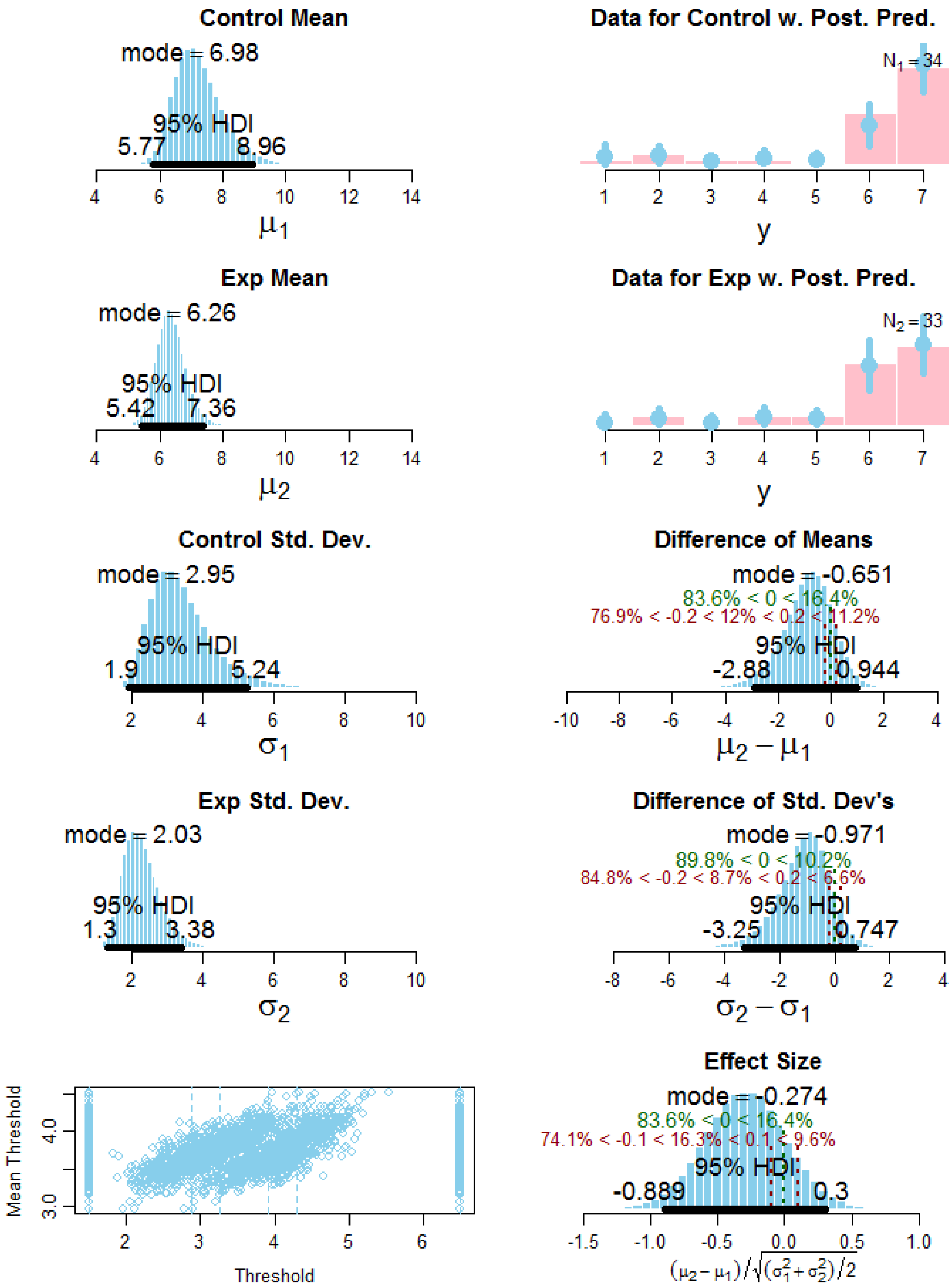
9. How would you rate your mental workload during the flight?

| Very Low | | | | | | Very High |
|---|---|---|---|---|---|---|
| **1** | 2 | 3 | 4 | 5 | 6 | **7** |



10. Having a notification of weather changes along the route of flight—together with the information on the weather presentation—is better than just having the weather presentation alone.

| **Totally Disagree** | | | | | | **Totally Agree** |
|---|---|---|---|---|---|---|
| **1** | 2 | 3 | 4 | 5 | 6 | **7** |



11. Did you experience discomfort from the fNIR device? No Yes

No = 61
Yes = 5

# Appendix D: Research Staff List

## Research Staff List

| Name | Role | Responsibility |
|---|---|---|
| Ahlstrom, Ulf | Test Lead | Manages the project: Lead developer of scenarios, change-detection experiments, test plan, data analysis, and technical report. Test conductor. |
| Bastholm, Robert | Human Factors Specialist | Implements fNIR recordings. Prepares training materials, data analysis, and technical report. Test conductor. |
| Caddigan, Eamon | Human Factors Specialist | Co-develops test plan, data analysis, technical report. Test conductor lead. |
| Dworsky, Matthew | Human Factors Specialist | Implements fNIR recordings. Develops change-detection stimuli, prepares training materials, test conductor. Data analysis, technical report. |
| Granich, Thomas | Software Engineer | Implements simulator system and cockpit data recordings. |
| Jackman, April | Technical Editor | Reviews, edits, and formats documents, reports, and templates, and prepares technical reports for publication and dissemination. |
| Johnson, Ian | WTIC Human Factors Lead | Provides pilot perspective. Coordinates on test plan and test efforts, technical review of test products and deliverables. |
| Kukorlo, Matt | Pilot Subject Matter Expert | Provides pilot perspective. Flight Scenario Developer. Simulation SME. |
| Kusza, Robert | Simulator Developer | Operates simulator systems, records cockpit data, and performs data backup. |
| Mutchler, Mark | Certification and small aircraft expertise | Provides pilot perspective. Assist in scenario development. |
| Ohneiser, Oliver | Human Factors Specialist, Software Engineer | Provides analysis software development. Technical report. |
| Pokodner, Gary | WTIC Program Manager | Tracks project, conducts interim reviews, and final acceptance of deliverables. |
| Rehman, Al | Manager, Cockpit Simulator Lab | Manages and maintains cockpit lab systems. Provides support in scheduling subject pilots for study. |
| Sultan, Roger | Safety | Provides pilot perspective. Assists with scenario development. Identifies any safety or documentation issues. Provides aeronautical standards and expertise. |