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

TRACON Controller Weather Information Needs:

III. Human-in-the-Loop Simulation

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16. Abstract

Hazardous weather conditions affect the National Airspace System (NAS) in many ways, including flight safety and system effectiveness. From a safety perspective, hazardous weather conditions contribute to aircraft accidents and fatalities (National Transportation Safety Board [NTSB], 1999a; NTSB, 1999b). From an operational perspective, hazardous weather conditions are very costly. In 1995, weather related delays cost airlines $4.1 billion and costs are only increasing ("Weather reports should be higher priority," 1995). In an effort to mitigate these effects, the Federal Aviation Administration (FAA) is improving the availability of advanced weather information at select Terminal Radar Approach Control (TRACON) facilities. However, the bulk of this weather information is only available to traffic management and supervisors for *strategic* use. TRACON controllers do not have direct access to advanced weather products. They maintain their Weather Situation Awareness (WSA) by receiving weather briefings from the supervisor and by viewing precipitation levels on their workstation. In the present study, we systematically investigated advanced weather tools and their impact on *tactical* operations in the TRACON domain. Our results showed an impact of advanced weather information on controller efficiency, with increases in sector throughput (completed flights) of 6% to 10%. By providing enhanced weather information at the workstation, we were able to enhance controllers' ability to detect approaching weather, monitor its movement, and understand its effect on future operations. In the field, this will increase controllers' efficiency for the timing of arrivals, for vectoring, for the adjustment of flow and sequencing, and for runway selection.

17. Key Words

Advanced Weather Displays, Efficiency, Human-in-the-Loop Simulation,
TRACON Controller Information Requirements, Weather Graphics,
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Executive Summary

Introduction

Hazardous weather conditions affect the National Airspace System (NAS) in many ways including flight safety and system effectiveness. From a safety perspective, hazardous weather conditions contribute to aircraft accidents and fatalities (NTSB, 1999a; 1999b). From a NAS operations perspective, hazardous weather conditions are costly. In 1995, weather related delays cost airlines $4.1 billion and costs are only increasing ("Weather reports should be higher priority," 1995).

In an effort to mitigate these effects, the Federal Aviation Administration (FAA) is improving the availability of advanced weather products at select Terminal Radar Approach Control (TRACON) facilities. In essence, these weather products provide detailed information about the presence of microburst, wind shear, and gust fronts, as well as the direction and speed of storm cells. However, the bulk of this weather information is only available to traffic management and supervisors for *strategic* use (Ahlstrom, 2004). TRACON controllers maintain their weather situation awareness (WSA) by receiving weather briefings from supervisors and by viewing six independent levels of precipitation on the Standard Terminal Automation Replacement System (STARS) Terminal Controller Workstation (TCW) or the ARTS Color Display. If the controller uses older TRACON display systems, he/she can only display two precipitation levels simultaneously (out of six possible). In addition, controllers receive reports of hazardous weather conditions that pilots encounter during flight.

Providing controllers with the capability to display advanced weather information could be one way to improve the ability of NAS to deal with adverse weather. However, although accurate and timely weather information is of utmost importance for the mitigation of delays and safety risks, it is not clear what types of information would be most useful for TRACON operations (Ahlstrom & Della Rocco, 2003). Furthermore, we know very little about the optimal display of this information or about the human factors issues associated with tactical operations (Ahlstrom, Keen, & Mieskolainen, 2004). Too much weather information could interfere with the perception of traffic data by providing redundant information and by causing display clutter. On the other hand, if we increase controller efficiency by providing immediate access to enhanced weather information, we could see benefits like increased traffic throughput, improved weather advisories to pilots, and reduced workload associated with controlling traffic during adverse weather conditions.

Method

In the present high-fidelity simulation, we investigated the impact of advanced weather information on controllers' *tactical* operations. We manipulated the display of advanced weather information and compared this to a control condition where controllers had no weather information (current field operations). The advanced weather information consisted of pre-recorded Integrated Terminal Weather System (ITWS) data from the Dallas Fort Worth (DFW) TRACON. During the human-in-the-loop simulation, we presented the weather information on the TCW or on an auxiliary weather information display system (WIDS). Eleven non-supervisory, full-performance level TRACON controllers volunteered as participants. We used a generic TRACON airspace with two adjacent sectors and employed standard operating procedures (SOP) developed for the simulation airspace. To allow an examination of the effects of advanced weather information, we included a procedure that assigned responsibility for keeping aircraft away from weather Levels 4, 5, and 6 to the controller. During simulation runs, two controllers operated traffic within the TRACON airspace. One controller was responsible for West operations, while the other controller was responsible for East operations. Controllers issued commands to simulation pilots and received additional information from an experimenter serving as a supervisor and subject matter expert (SME). The simulation pilots maneuvered aircraft using keyboard commands and communicated with the controllers using proper ATC phraseology and procedures. Because controllers rely heavily on pilot reports (PIREPs) during adverse weather conditions, we displayed weather information on simulation pilots' workstations. By providing the same precipitation information to controllers and simulation pilots, we enhanced the WSA and allowed for feedback that is more realistic during controller/pilot communications. To measure the workload associated with the use of advanced weather tools, controllers provided real-time workload ratings using the Air Traffic Workload Input Technique (ATWIT).

Results

We found a significant impact of advanced weather information on controller efficiency. With advanced weather information at the workstation, controllers increased the average sector throughput (completed flights) by 6-10% compared to the Control condition where no weather information was available. By providing enhanced weather information at the workstation, we enhanced controllers' ability to detect approaching weather, monitor its movement, and understand its effect on future operations. This increased controllers' efficiency for timing of arrivals, for vectoring and adjustment of flow and sequencing, and for runway selection.

In addition to increased sector throughput, we also found benefits for pilots when controllers had access to enhanced weather information. During the simulation, controllers issued weather sequences as they became available, reported storm intensity and movements, delivered reports about changing conditions, and explained reasons for approach changes to pilots when they were necessary. In short, pilots could benefit from increased controller WSA and the corresponding improvements in weather advisories. Increased WSA also had a positive effect on controller working conditions. Although controllers rated their instantaneous workload as low during all simulation runs, controllers' post-scenario ratings showed a significant reduction in overall workload during the weather tool conditions compared to the Control condition.

Although our findings indicated that presenting weather information on both the WIDS and TCW was beneficial to controllers, we did see differences in the simulation data that could possibly be due to presentation mode idiosyncrasies. For example, both presentation modes differed with respect to the spatial and temporal presentation of traffic and weather data, and in the potential for creating display clutter. During WIDS conditions, we found that controllers performed significantly more heading commands compared to TCW conditions. This could possibly have been due to the spatial separation of weather and traffic data, which may have resulted in a larger number of corrective heading commands by controllers during WIDS operations. Another issue related to the spatial separation of data is the amount of 'heads-up' time for controllers using the WIDS display. Potentially, controllers could have spent a large amount of time looking up at the WIDS, time not spent focusing on the traffic data. However, this did not seem to be the case during our simulation. Using point-of-gaze (POG) data from oculometer recordings, we found that controllers had an average total viewing time on the WIDS display of 1.61 min during Weather Scenario 1, and 4.52 min during Weather Scenario 2. With regards to weather tool usage, we found a tendency for controllers to display advanced weather products for longer durations during WIDS conditions when compared to TCW conditions. This interaction pattern was likely the result of increased display clutter that would have resulted from superimposing traffic and weather data on the TCW. Despite these idiosyncratic effects, it seems controllers can safely and effectively use both presentation modes for tactical operations. Based on subjective reports from controllers, we identified no clear preference for either presentation mode. Both the weather presentation on WIDS and TCW were preferred over receiving information from the supervisor. Controllers who reported preferring WIDS stated that they liked WIDS because weather information was instantly available but did not interfere with the traffic display. Those controllers who preferred receiving weather information on the TCW felt that on the TCW, there was less work involved in correlating weather information with current aircraft positions, and that there was no need to divert attention away from the traffic when viewing weather information.

Conclusion

The purpose of the present study was to evaluate the impact of advanced weather information on TRACON controller's tactical operations. We found that providing controllers with the capability to display advanced weather information increased controllers' efficiency for the timing of arrivals, for vectoring and adjustment of flow and sequencing, for runway selection, and for improving weather advisories to pilots. Although some types of weather information may provide more benefits for tactical operations than others do, *we want to emphasize that any timely and accurate advanced weather information not currently at the workstation could benefit controller WSA*. By reducing the uncertainty about weather conditions, controllers can make better decisions that will positively affect the safety and efficiency of terminal operations.

1. Introduction

It is important that NAS users have accurate and timely information about weather to aid tactical and strategic planning for safe operations because adverse weather conditions affect the National Airspace System (NAS) in many ways including flight safety and system effectiveness. The National Transportation Safety Board (NTSB, 1999a) reports that 23% of major airline and cargo carrier (Part 121) accidents were weather-related during 1999. For commercial air carriers (Scheduled Part 135), 38% of the accidents were weather-related, and for airplanes and helicopters (Nonscheduled Part 135), the rates were 23% and 47%, respectively. For general aviation (GA), weather conditions were a factor in 19% of all accidents (NTSB, 1999b). Hazardous weather is also costly. In 1995, weather related delays cost airlines $4.1 billion and costs are only increasing (“Weather reports should be higher priority,” 1995).

In the current NAS, terminal controllers maintain their weather situation awareness (WSA) by receiving weather briefings from the supervisor and by viewing six independent levels of precipitation on the Standard Terminal Automation Replacement System (STARS) Terminal Controller Workstation (TCW) or the Automated Radar Terminal Systems (ARTS) color display. If the controller uses older Terminal Radar Approach Control (TRACON) display systems, he/she can only display two precipitation levels simultaneously (out of six possible). In addition to this information, controllers get pilot reports of hazardous weather conditions that are encountered during flight.

The present paper is the third study in a project that investigated weather information needs for TRACON controllers. The initial phase of the project consisted of a literature review summarizing current research on weather displays for controllers and pilots, weather related controller/pilot communications, and weather situation awareness (Ahlstrom & Della Rocco, 2003). The outcome of this review points to several problems in the areas of weather information needs and weather information displays. First, empirical research is lacking on the use of weather information displays for tactical operations. Second, little is known about optimal presentation formats for advanced weather information. Third, no research has empirically evaluated possible benefits or display problems associated with displaying advanced weather information on the controller display. Furthermore, there are no empirical guidelines for how controllers would use advanced weather information for tactical operations.

Much research has focused on developing weather displays for the cockpit (Arend, 2003). Far less research has been devoted to the development of weather displays for TRACON controllers. Furthermore, researchers have focused on *how* to display weather information (e.g., computer-human interface [CHI] issues) rather than *what* information to display (Ahlstrom & Della Rocco, 2003). The CHI designs for advanced weather products developed by the NAS Human Factors Group (2002) are examples. The group created weather data graphics for the STARS TCW. Although the study examined the best ways to display these products in the user interface, no empirical data on the usefulness and benefits from these weather products are available. Therefore, the TRACON controllers’ weather information needs and the possible effect of these products on controller WSA are largely unknown. Before investing in the display of available information at the risk of too much clutter and redundant information, it is important to develop empirical data to guide the investment effort.

In the second project phase during July 2003, researchers assembled a group of five TRACON controllers and six airline pilots to examine the current use of weather information in the

TRACON domain. During group sessions, we discussed weather phenomena and the impact on controller and pilot operations. To structure these discussions, we used the framework of Cognitive Work Analysis (CWA) (Vicente, 1999), a method developed to analyze complex socio-technological work domains. The outcome of the CWA analysis revealed several information needs for the TRACON controller (Ahlstrom, 2004). For example, at the controller workstation, there is a lack of a graphical display of weather with short-time forecast capabilities. Furthermore, there is also a lack of timely and accurate wind information. These two information sources are especially important for the controller during thunderstorms.

2. Purpose

The purpose of the present study is to obtain empirical answers to the following questions.

1. What weather information benefits controllers during tactical operations?
2. Where should this weather information be displayed?
3. Can enhanced weather displays increase the number of instrument operations during adverse weather conditions?
4. Can enhanced weather displays improve severe weather avoidance?

We hypothesized that immediate access to enhanced weather information would increase controller efficiency, increase the number of instrument operations (i.e., aircraft passing the final approach fix), improve controller weather advisories to pilots, and reduce the workload associated with controlling traffic during adverse weather conditions.

3. Method

3.1 Participants

Eleven nonsupervisory, full-performance level TRACON controllers participated in the study (*M* experience = 12 years, *SD* = 4.6 years). Controllers were solicited from nationwide ARTS II, ARTS III, and STARS equipped facilities. All controllers held a current medical certificate. Table 1 shows the descriptive statistics for the biographic questionnaire data collected from these controllers.

Table 1. Biographic Questionnaire Data for Terminal Controllers

	Mean Years (*SD*)
What is your age?	41.26 (7.54)
How long have you worked as an ATCS (Include both FAA and military experience)?	15.05 (5.19)
How long have you worked as an ATCS for the FAA?	14.19 (4.77)
How long have you been a Certified Professional Controller (or Full Performance Level Controller)?	12.08 (4.58)
How long have you actively controlled traffic in a terminal environment?	12.49 (4.67)

There are multiple sources of weather information in terminal facilities. The STARS and the Color ARTS (CARTS) systems present traffic data and six precipitation levels to controllers.

The Information Display System 4 (IDS4) provides controllers with access to information that includes maps, charts, and connections to FAA and National Weather Service (NWS) systems. Wind instruments provide information about terminal winds. The Digital Altimeter Setting Indicator (DASI) displays the altimeter-setting indicator for air traffic operations. Runway Visual Range (RVR) is a measurement of the maximum distance at which the runway, or specified lights or delineation markers can be seen from a position above a specified point on its centerline. The Automated Surface Observing System (ASOS) provides weather observations on the current temperature, dew point, wind, altimeter setting, visibility, sky condition, and precipitation. The Stand Alone Weather Sensors (SAWS) collects information on surface weather data including wind speed, wind direction, wind gusts, altimeter settings, temperature, and dew point. The Integrated Terminal Weather System (ITWS) provides information on current weather conditions and weather conditions for 30 minutes in the future, including information on wind shear, lightning, microburst detection and predictions, storm cell intensity and direction, and winds in the terminal area. The Weather Systems Processor (WSP) provides low-cost wind shear detection equipment at airports with medium air traffic density. The Terminal Doppler Weather Radar (TDWR) provides information on hazardous wind shear in and near airport terminal approach and departure corridors.

Most controllers had limited familiarity with these terminal weather products, and only a few controllers reported having access to storm and forecasting products at their home facility (see Table 2). In cases where these products were available, they were located at the supervisor position or a location that was separate from the controller workstation.

Table 2. Controller Access to Terminal Weather Products at their Home Facility

Product	**Number of controllers reporting access to product (*N* = 11)**
STARS	4
CARTS	2
IDS-4	8
Wind instruments	10
DASI	11
RVR	10
ASOS	9
SAWS	2
ITWS	2
WSP	2
TDWR	3

3.2 Simulation Setup

A team of research psychologists and TRACON subject matter experts (SMEs) conducted the simulations in the Research Development and Human Factors Laboratory (RDHFL) at the William J. Hughes Technical Center. The simulation configuration consisted of the Distributed Environment for Simulation, Rapid Engineering, and Experimentation (DESIREE) and the Target Generator Facility (TGF). DESIREE emulates STARS functions and receives input from the TGF to display radar targets. During the simulation, we presented weather information on the STARS TCW or the Weather Information Display System (WIDS). WIDS is an auxiliary flat-panel display for the display of precipitation and advanced weather information (Ahlstrom, Keen, & Mieskolainen, 2004). To display prerecorded weather information from the ITWS, an ITWS simulator feeds DESIREE with a stream of prerecorded ITWS data at its original speed. DESIREE receives this stream, and provides multiple views of advanced weather data either on the WIDS or the STARS TCW.

Two controllers operated the sector traffic for each simulation run. One controller was responsible for West operations, while the other controller was responsible for East operations. The controllers issued commands to simulation pilots and received additional information from an experimenter serving as a supervisor and SME. The simulation pilot workstations were located in a remote room in the same building. The simulation pilots maneuvered aircraft using simple keyboard commands and communicated with the controllers using proper ATC phraseology and procedures. The controller STARS workstations were set up in one experiment room. An SME was positioned behind each controller to make observations. Research psychologists operated the data collection equipment and an oculometer workstation. For all traffic scenarios, the West side controller wore an oculometer (Applied Science Laboratories Inc., 2004) consisting of an eye and head tracking system. For more detail, the oculometer hardware and software is described in previous research (Willems, Allen, & Stein, 1999; Willems & Truitt, 1999). The oculometer system allowed the researchers to monitor controller eye movements while they controlled traffic using the advanced weather displays.

During simulation runs, the controllers provided workload ratings using the Air Traffic Workload Input Technique (ATWIT), a real-time unidimensional workload rating method. ATWIT provides an unobtrusive and reliable means for collecting self-report workload ratings as the controller manages air traffic (Stein, 1985, 1991). A SUN workstation and a 10-button keypad collected and recorded controller responses. The controllers indicated their instantaneous workload by pressing one of the keypad buttons labeled from 1 (low workload) to 10 (high workload). The system prompted controllers for input every five minutes by emitting several beeps and lighting the buttons on the keypad. Controllers had 20 seconds to respond by pressing one of the ten buttons. If there was no response within 20 seconds, ATWIT defaulted to a digit indicating that there was no response.

3.3 Air Traffic Standard Operating Procedures

For the present study, we used standard operating procedures (SOP) developed for the simulation airspace. These procedures dictate operational responsibilities for the area of jurisdiction (AOJ), separation, controller responsibilities, equipment, data entries, emergencies, coordination, handoffs, reduced longitudinal separation on final approach, simultaneous independent ILS approaches, and approaches to satellite airports. Most important for the present study, however, was the inclusion of an experimental procedure that assigned responsibility for keeping aircraft away from weather Levels 4, 5, and 6 to the controller.

3.4 Advanced Weather Information

The NAS Human Factors Group (2002) proposed CHI designs for several advanced weather products for TRACON operations. These products provide detailed information about storm cells and winds. The data for all of these weather products are derived from external weather processor systems like the ITWS, the WSP, and the Low-Level Wind Shear Alert System.

For the current simulation, we used most of the weather products described by the NAS Human Factors Group (2002). In addition, we also used graphical animations of weather cell movements (2-20 min history and 30 min prediction) and graphical representations of short-term precipitation forecasts (15 min prediction). Throughout this document, we refer to these weather products as *advanced weather products* to distinguish them from the precipitation levels currently available on the TCW. Finally, we also used common terminal weather advisories (e.g., RVR, Aviation Routine Weather Report [METAR], Airman's Meteorological information [AIRMET], and Significant Meteorological advisory [SIGMET]).

The advanced weather products are identical to or closely resemble the design of weather graphics found on the ITWS (Evans & Ducot, 1994). Other types of weather data (i.e., METAR, AIRMET, and SIGMET) are identical to or similar to web-based weather information provided by other sources (e.g., the Aviation Digital Data Service). In the next sections, we provide examples of the weather graphics and a description of symbols and colors (NAS Human Factors Group, 2002).

3.4.1 Weather Loop

The Weather Loop prototype is an animated loop of all precipitation levels with previous location (history), current location, and a 30 min forecast. The history loop segment is defined in scenario time and increases from zero up to a maximum of 20 minutes. The graphical format is identical to the *Precipitation Forecast* below, but it consists of ten frames. The Weather Loop runs continuously upon activation, and if not stopped, times out after 30 seconds.

3.4.2 Precipitation Forecast

The Precipitation Forecast prototype is a graphical two-frame apparent motion sequence of all precipitation levels from the current position to the forecasted position 15 minutes into the future (see Figures 1a and 1b). After displaying the forecasted position for 2 sec, the display times out.

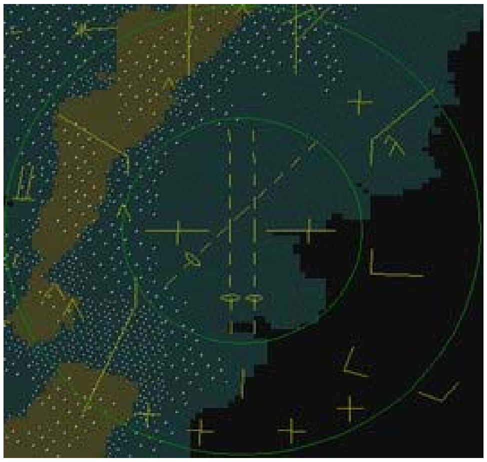


Figure 1a. Sample of current position.

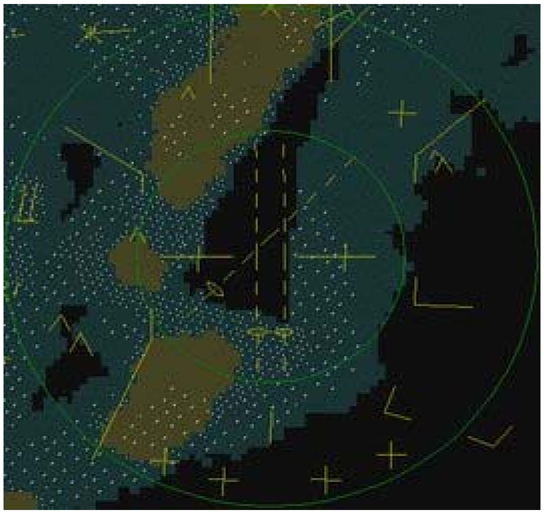


Figure 1b. Sample of 15 min forecast.

3.4.3 Storm Motion and Extrapolated Position

The Storm Motion product indicates the speed and direction of storm cells in the terminal area (see Figure 2). The storm extrapolated position provides leading-edge contours for cells and cell groups and extrapolates these contours 10 and 20 minutes into the future. A white arrow of constant length defines the direction of cell motion. The speed of the cell appears in knots as white numerals. A solid cyan line indicates the leading edge of a cell or cell group. A dashed cyan line indicates the extrapolated position of that cell in 10 minutes. A dotted cyan line indicates the extrapolated position of the cell in 20 minutes. The Storm Motion tool is displayed continuously upon activation (no time out).

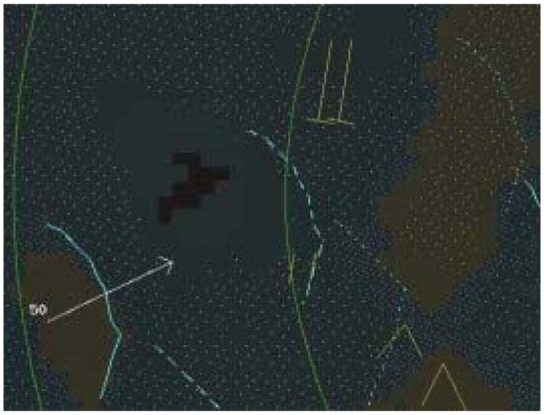


Figure 2. Storm Motion and extrapolated position.

3.4.4 Gust Front and Wind Shift

The Gust Front and Wind Shift products indicate the location of gust fronts (see Figure 3) and the speed and direction of winds behind the front. Gust fronts are represented as three purple lines. A solid purple line indicates the current gust front position. A dashed purple line indicates the extrapolated position of the front in 10 minutes. A dotted purple line indicates the extrapolated position of the front in 20 minutes. A nonscaling purple arrow and numerals represents the direction and speed in knots of the wind shift. The Gust Front tool is displayed continuously upon activation (no time out).

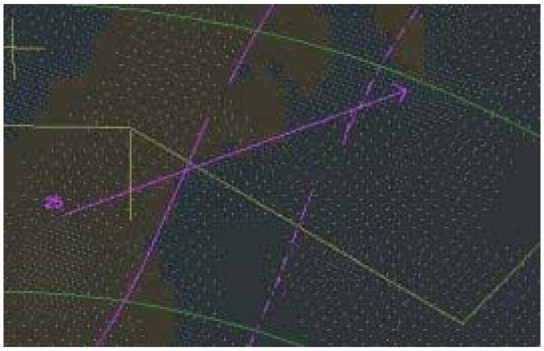


Figure 3. Sample of Gust Front and Wind Shift.

3.4.5 Microburst

A Microburst is a strong wind occurring near the ground, generated by a strong storm downdraft. A Microburst indication occurs when the change in wind speed is greater than or equal to 30 knots. The Microburst symbol is a 50% filled red circle with white numerals (see Figure 4). The location of the center of the circle reflects the location of the microburst. The size of the circle reflects the horizontal size of the microburst area. The text represents the change in wind speed, in knots, associated with the microburst. When Microburst information was available in the prerecorded ITWS data, the simulator displayed the Microburst symbol automatically. There was no option for the controller to toggle this information on or off. WS 1 contained four Microbursts that were displayed for an average of 1.7 min (*SD* = 0.97). WS 2 only contained one Microburst that was displayed for approximately 6 sec at the end of the scenario.

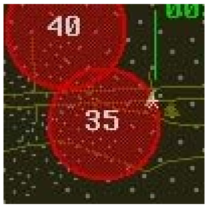


Figure 4. Sample of Microburst.

3.4.6 Wind Shear

The Wind Shear product is similar to the Microburst product, except it is defined as a change in wind speed equal to or greater than 15 but less than 30 knots. A wind shear is represented as an unfilled red circle with white numerals (see Figure 5). The location of the center of the circle reflects the location of the wind shear. The size of the circle reflects the size of the wind shear. The text represents the change in wind speed in knots associated with the Wind Shear. When Wind Shear information was available in the prerecorded ITWS data, the simulator displayed the Wind Shear symbol automatically. There was no option for the controller to toggle this information on or off. WS 1 contained 15 Wind Shear alerts that were displayed for an average of 4.6 min (*SD* = 3.08). WS 2 contained six Wind Shear alerts that were displayed for an average of 1.7 min (*SD* = 0.97).

Figure 5. Sample of Wind Shear.

A common characteristic among these weather products is their heritage from classic meteorological data visualizations used for *strategic* rather than *tactical* operations. As such, these visualizations have a long tradition but are likely subject to future refinement for use in tactical operations. There is also an unknown issue with regards to optimal weather tool groupings. No previous research has investigated combinations of weather tools to assess optimal presentation formats (Ahlstrom et al., 2004).

As mentioned earlier, no empirical data exist on the use of advanced weather information for tactical TRACON operations (Ahlstrom & Della Rocco, 2003). Ideally, researchers could compare the effect on performance for each one of these weather products to a control condition, for pair-wise differences between weather products, and finally, for all weather products used in combination. However, such a design would require means that are beyond the scope of the present study.

In the present simulation, we employed a research design where the controllers were able to use all of the advanced weather products during simulation runs except during control conditions. The primary difference between the two conditions where controllers had access to advanced weather products was whether they received the information on the STARS TCW or WIDS. Rather than presenting controllers with predefined weather tool groupings, we explored how controllers used advanced weather products as they controlled traffic during different weather scenarios. We hypothesized that controllers, after adequate weather tool training, would only use weather tools that provide useful information. Furthermore, some weather tools and some tool combinations might be useful during certain periods of the scenarios, with other tools and other combinations being useful in other periods. To capture these trends, we recorded every controller interaction with weather tools during simulation runs. On both the WIDS and the TCW, weather tools were toggled on and off by menu selections using the mouse (WIDS) or trackball (TCW). All interactions with WIDS and STARS weather tools were time stamped and subsequently correlated with oculometer data and other system measures from the scenario.

The controllers rely heavily on pilot reports (PIREPs) during adverse weather conditions. Therefore, researchers and software engineers at the RDHFL collaborated with TGF software engineers to provide weather information to the simulation pilots. By providing the same precipitation information to controllers and simulation pilots, we enhanced the WSA and allowed for more realistic feedback during controller/pilot communications. Figure 6 shows an example of a simulation pilot display used during the simulation.

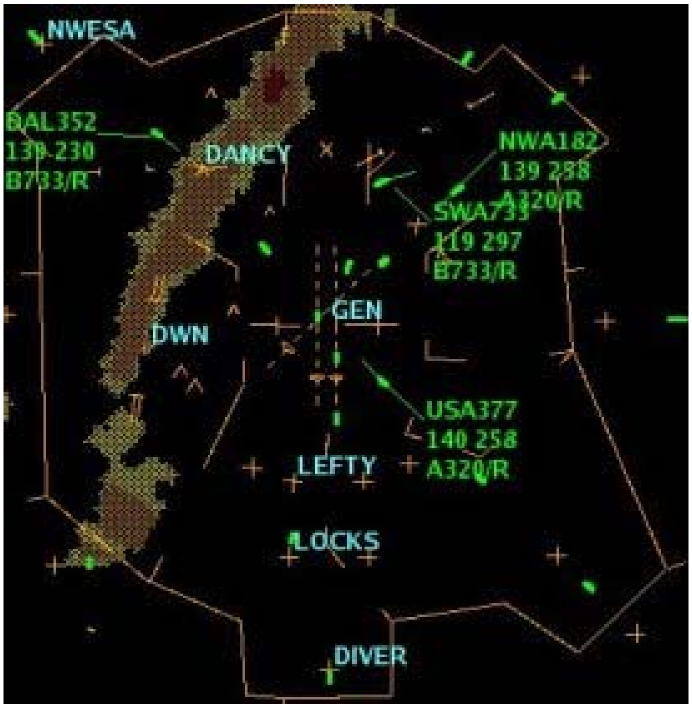


Figure 6. A situation display for simulation pilots showing traffic and weather data. Precipitation Levels 4, 5, and 6 are displayed.

3.5 GENERA TRACON Airspace

For the present simulation, the research team used a generic TRACON airspace (GENERA) to study the potential benefits from advanced weather displays. By creating generic airspace scenarios, we were able to configure air traffic patterns that fit our prerecorded ITWS weather scenarios. Because of the generic nature of the airspace, it was easy for TRACON controllers to learn and required less training time (Guttman & Stein, 1997; Guttman, Stein, & Gromelski, 1995). In addition, we could recruit controllers from a number of TRACON facilities across the United States. Figure 7 presents an airspace map for the GENERA airspace.

The airspace extended for approximately 70 nm from north to south, and approximately 60 nm from west to east. Four en route sectors (GENERA Center), each with a separate arrival fix, surrounded the GENERA airspace. The primary arrival flows to runway 36L came from the south and northwest arrival fixes. The primary arrival flows to runway 36R came from the southeast and the northeast arrival fixes. Runway 5 was available for instrument approaches as needed. Runways 36L and 36R were also used for departures during the simulation. However, the departure sector worked independently of the GENERA arrival sectors.

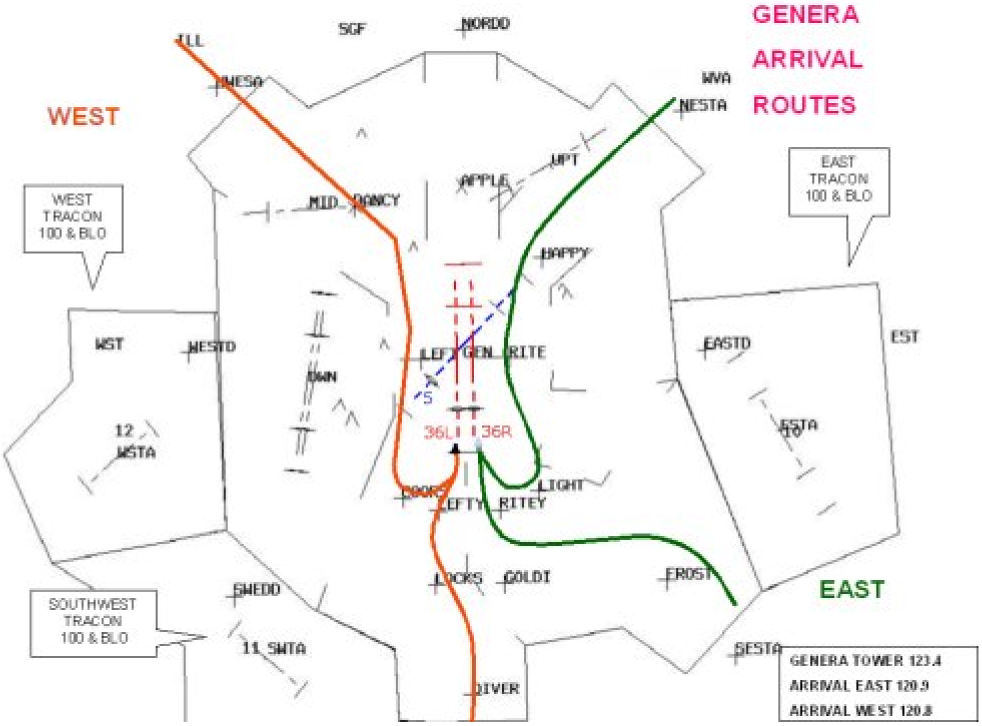


Figure 7. The GENERA TRACON airspace.

3.6 Traffic Scenarios

The research team designed traffic scenarios with moderate traffic levels. Based on input from SMEs, we determined that a moderate traffic level with adverse weather conditions would keep the controller busy but not overwhelmed. The team prepared six one-hour scenarios with an equal number of arrivals and departures. All practice scenarios included 50 aircraft (with a traffic mix of heavy = 17%, air carrier = 81%, and GA = 2%) and all test scenarios included 88 aircraft (with a traffic mix of heavy = 17%, air carrier = 78%, and GA = 5%). However, we assigned different callsigns to each scenario.

3.7 Scripted Events

The researchers and SMEs scripted certain events that occurred at set intervals during the simulation runs. These events included position relief briefing, SIGMET report, and Aviation Selected Special Weather Report (SPECI), and RVR updates.

4. Procedure

Controllers arrived at the RDHFL in pairs for three days of simulation runs. Monday and Friday were travel days. Tuesday consisted of a project briefing, sector training, the completion of a background questionnaire, and weather tool training. Controllers received one day of training on GENERA airspace and the use of advanced weather information (WIDS and TCW). At the start of the weather tool training, controllers completed a training manual under the supervision of SMEs and research psychologists. The manual described the use and purpose of each weather tool, specified the information provided by each tool, and explained how to activate and de-activate the tools. Upon completion of the training manual, controllers practiced using the weather tools on both the WIDS and the TCW. Controllers familiarized themselves with the weather tools and simulation hardware by performing the initial practice session without any traffic on the TCW display. During subsequent training sessions, controllers ran traffic in two different 30-minute scenarios while using advanced weather information presented on either the WIDS or the TCW. All controllers participated in a minimum of five practice scenarios. Upon completion of the weather tool training, all controllers were proficient in the use of all weather tools. None of these traffic and weather training scenarios were used in the simulation. Additionally, on the first day of training researchers assigned controllers to the GENERA East and West positions. Because the West controller was equipped with the oculometer during all simulation runs, the West controller wore the equipment while participating in training runs. Wednesday and Thursday were devoted to the six simulation runs. During simulation runs, the controllers worked traffic under adverse weather conditions. After each scenario, the controllers completed questionnaires to evaluate the impact of the weather presentation on controller performance, workload, and WSA (Appendix A). In addition, SMEs made over-the-shoulder observations during the simulation to further assess the impact of the weather displays on controller performance. An automated data collection system recorded system operations and generated a set of standard ATC simulation measures that included safety, capacity, efficiency, and communications measures. The entire simulation was audio-video recorded in case researchers needed to reexamine any important simulation events. At the end of the last simulation run, the researchers held an exit debriefing and the controllers completed an exit questionnaire (Appendix B).

5. Simulation Design

The present study used a 3 (display location) x 2 (weather scenario) x 2 (sector) repeated measures design. Display location and weather scenario were within-subjects variables, while sector was a between-subjects variable. We counterbalanced the presentation order of the simulation conditions by means of a randomized block design.

5.1 Independent Variables

While empirical performance data is available for static displays of single and superimposed radar and chart images (Donderi & McFadden, 2003), no empirical data are available for dynamic air traffic and weather data. Superimposing multiple sets of weather data on traffic data can be advantageous in that a lot of information can be viewed directly (Wickens & Carswell, 1995 - see Figure 8a). However, it can also lead to display clutter and thereby hamper information *pick-up* (Yeh & Wickens, 2001). With an increasing number of display objects like weather data (e.g., six levels of precipitation and storm information etc.), traffic data (e.g., text in data block), sector map details (e.g., boundaries, fixes etc.), and other types of text information (e.g., lists, wind speed etc.), the chances of creating display clutter increases greatly (Phillips & Noyes, 1982). If weather data components are spatially separated from the traffic data, there is less chance for display clutter and interference with information retrieval (see Figure 8b). However, such separation can potentially reduce the ease by which a controller gains a quick overview of traffic patterns and weather hazards (see Sauer, Wastell, Hockey, Crawshaw, Ishak, & Downing, 2002 for a related study of display integration on ships' bridges).

According to the Office of Inspector General (2002, February), controllers identified a wide range of human factors issues related to displaying Weather and Radar Processor (WARP) precipitation levels on *en route controller displays*. For example, there were problems with the quality and reliability of the weather display due to the intensities of precipitation and color. The controllers also anticipated that future problems were likely to surface since new issues could emerge as controllers gained experience with the colored weather graphics and observed how the graphics interact with their traffic data. For these WARP displays, the problems occurred with only *three levels* of precipitation. For the current simulation with STARS TCW, we used *six levels* of precipitation in addition to advanced weather graphics. Therefore, the assessment of the effect on performance from display location of advanced weather information is critical. In the current simulation, we manipulated the display location of advanced weather information in three conditions.

Figure 8a. Advanced weather information and traffic data presented simultaneously on the TCW.

Figure 8b. Advanced weather information presented on the WIDS (top display) and traffic data on the TCW (bottom display).

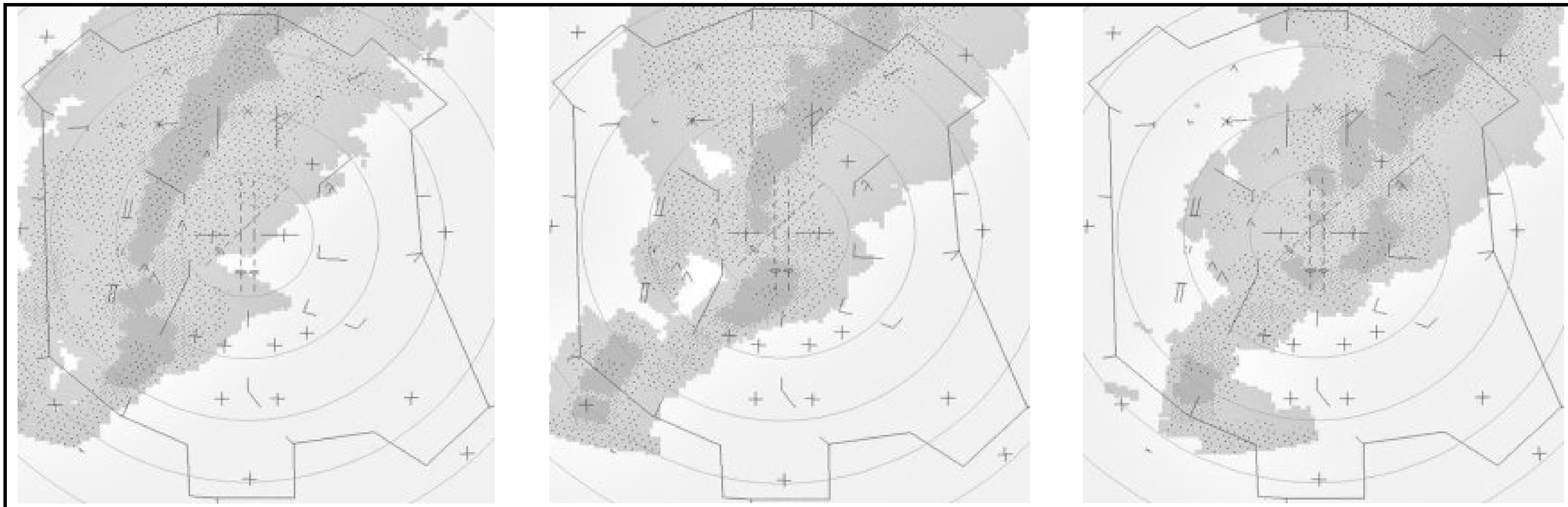
In the WIDS condition, we displayed advanced weather information on the WIDS. The six STARS precipitation levels were available on the TCW. During the simulation, the WIDS display was located above the TCW (Figure 8b).

In the TCW condition, we display advanced weather information and the six STARS precipitation levels directly on the TCW (Figure 8a). The WIDS was not used during this simulation condition.

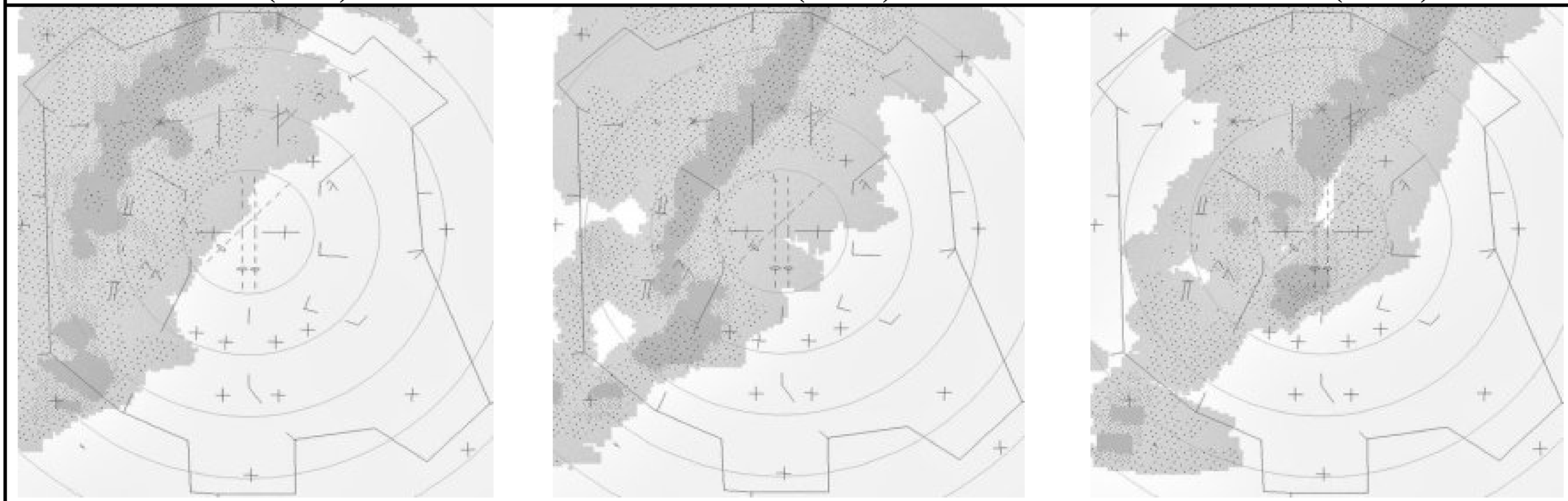
In the Control condition, we did not present any advanced weather information to the controller. However, the six STARS precipitation levels were available on the TCW. The WIDS was not used during this simulation condition. This control condition with only precipitation information represents current TRACON operations in the field, although the display format of precipitation varies with different terminal systems.

We used two sector positions during the simulation, the GENERA West and East.

Storms are multifaceted phenomena with intricate relationships between precipitation, cell movements, and the speed and direction of winds. For high-fidelity simulation purposes, it was therefore critical to use real weather data that kept these relationships intact. For the present simulation, precipitation levels and advanced weather data consisted of prerecorded ITWS data from the Dallas Fort Worth (DFW) TRACON. To create some variation in the weather scenarios, we used two samples (Weather Scenario [WS] 1 and 2) of prerecorded ITWS data. Both weather samples contain the same ITWS weather products, were similar in nature (i.e., contained line storm parts, weather cell growth and decay, and a high degree of weather cell Level 4, 5, and 6 ‘pop-ups’), but differed in the overall spatial and temporal characteristics. WS 1 exhibited a higher degree of storm cell ‘pop-ups’ affecting Runway 36L, 36R, and Runway 5, and these conditions occurred earlier and lasted longer throughout the scenario. In WS 2, Runways 36L and 36R were affected later on in the scenario and Runway 5 was open to a larger extent throughout the entire scenario compared to WS 1. Figure 9 gives an illustration of the storm characteristics for WS 1 and WS 2. For a description of the scripted SIGMET, SPECI, and RVR updates, see Appendices C and D.



WS 1 (1 min) WS 1 (25 min) WS 1 (50 min)



WS 2 (1 min) WS 2 (25 min) WS 2 (50 min)

Figure 9. Illustrations of the storm motion (the spatio-temporal change in precipitation levels) for WS 1 (top) and WS 2 (bottom) as it moves across GENERA airspace. Three frames from each 50 minute scenario are shown in the figure (1 min, 25 min, 50 min).

5.2 Dependent Variables

The dependent measures in the present study correspond to the critical areas of severe weather avoidance, efficiency, safety, communication, WSA, and the use of weather tools.

1. For the assessment of **severe weather avoidance**, we recorded the number of aircraft penetrating areas of severe weather (i.e., precipitation Levels 4, 5, and 6) and the duration of these penetrations.

2. For the assessment of **efficiency** from enhanced weather displays, we recorded the following variables:

    a. Number of instrument operations (i.e., completed flights),
    b. Distance flown,
    c. Number of terminal holds,
    d. Duration of terminal holds,
    e. Number of altitude commands,
    f. Number of heading commands,
    g. Number of speed commands, and
    h. Number of handoffs.

3. For an assessment of **safety of operations**, we recorded loss of separation and wake turbulence violations.

4. For an assessment of **communications**, we recorded the number and duration of push-to-talk (PTT) communications.

5. For an assessment of controller **WSA**, SMEs assessed the characteristics of weather-related communications between the controller and simulation pilots.

6. For an assessment of the use and benefits of **advanced weather information**, we recorded every weather tool interaction during the simulation.

In addition to these objective measures, we gathered subjective measures that encompass safety, workload, efficiency, and communications. These measures include SME over-the-shoulder performance ratings, ATWIT ratings, modified NASA Task Load Index (TLX) ratings, and controller responses to post-scenario questionnaires.

5.3 Data Analysis Description

Traditionally, researchers often start the data analysis by performing unfocused significance tests (i.e., omnibus tests) to screen for differences in the data. If a significant result is found, the data are subjected to conservative post hoc procedures for pair-wise comparisons. Other researchers employ multivariate analysis of variance (MANOVA) when analyzing repeated-measures data (Myers & Well, 2003; O'Brien & Kaiser, 1985), due to potential inflated Type I error rates (incorrectly rejecting a true null hypothesis) when the sphericity assumption is violated. Although these procedures are potentially informative, they are not the most efficient methods for analyses where researchers have specific predictions of the experimental outcome (Jones & Tukey, 2000; Levin & Neumann, 1999; Loftus, 1995, 1996, 2004; Myers & Well; Wilkinson & Task Force on Statistical Inference, 1999). Many statisticians have pointed out that these Null Hypothesis Significance Tests (NHSTs) often lead to an increase in Type II error rates (failing to reject a false null hypothesis) (Cohen, 1994; Schmidt, 1996).[1] The American Psychological Association (APA) and the Task Force on Statistical Inference (TFSI) (American Psychological Association, 2001; Wilkinson & Task Force on Statistical Inference., 1999) have recently addressed issues related to NHST. They and others (Cohen, 1994; Nix & Barnette, 1998; Schmidt, 1996; Tryon, 2001) have pointed out many issues related to standard NHSTs. Tests of significance do not provide any information about: the probability of successful replication (i.e., power), the importance or size of an effect, and the absence of any effect (i.e., accepting the null).

A more powerful approach for researchers is the use of focused preplanned comparisons, (i.e., *contrasts)*, which analyze specific a priori hypotheses directly (Furr & Rosenthal, 2003a, 2003b). By using contrast analysis, we can perform significance tests that directly relate to the hypothesis under investigation. We have used repeated-measures contrast analyses on our data throughout this paper. By using repeated-measures contrasts, we also avoid sphericity problems associated with repeated-measures designs by converting multiple measures to a single contrast score. Based on current recommendations of the APA and the TFSI, we will be reporting point estimates, a measure of effect size, and confidence intervals.

Although several types of contrast analyses are available, the procedures for computing repeated-measures contrasts are straightforward. Appendix E provides an outline of the computational procedures used in our analyses. In the present study, the main directional hypothesis was that providing weather information to controllers (WIDS and TCW conditions) would increase their efficiency and performance. Where we specifically predicted an increase, we tested the hypothesis by using a *one-tailed* test of the contrast $\lambda_p = .5(\text{WIDS}) + .5(\text{TCW}) -1(\text{Control})$. This contrast reflected the prediction that providing advanced weather information to controllers would be better than providing no information. It also reflected, in the equal weighting of WIDS and TCW, a lack of a priori knowledge as to whether this benefit would differ in strength for the WIDS and TCW conditions.

However, in some instances where we predicted an effect of weather information, we had no a priori knowledge leading us to predict the direction of this effect. For instance, we might hypothesize that controller-pilot communications in the weather tool conditions would be more frequent and longer than in the Control condition because there might be more weather information to convey to pilots. However, we might also hypothesize that communications would be less frequent and shorter in the weather tool conditions due to an increase in routing efficiency when using weather tools. In this instance, we tested the nondirectional hypothesis by using a *two-tailed* test of the contrast $\lambda_p = .5(\text{WIDS}) + .5(\text{TCW}) - 1(\text{Control})$. A two-tailed test reflects the prediction that controller performance when using weather tools would differ from when they did not have access to these tools.

We also wanted to assess whether there was an effect on controller performance related to the display location of advanced weather information. Because we had some reasons to believe that we might find differences in performance based on where weather information was displayed,

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[1] Although the multivariate methodology avoids problems with sphericity and inflated Type I error, it suffers even more severely from inflation of Type II error rates. Because there are methods that correct degrees of freedom (*df*) when the data violates sphericity, we recommend using these corrections in all but the most severe cases (see Algina & Keselman, 1997, for specific recommendations).

but had no a priori expectation related to the direction of this effect, we tested this nondirectional hypothesis by using a two-tailed test of the contrast 1(WIDS) - 1(TCW).

To complement these analyses, we also performed exploratory analyses as they offered opportunities for new and unexpected insights. However, these exploratory analyses were not founded on a priori hypotheses or assumptions about possible effects. Because these exploratory analyses were not founded on any hypothesis, they were always nondirectional (note, however, that not all nondirectional tests are exploratory). We performed these analyses on simulation outcomes to address ambiguities, or to conduct more in-depth analyses on certain simulation outcomes. For example, we used exploratory analyses to examine differences in the frequency and duration of tool usage and the frequency and duration of precipitation level use in the weather tool conditions. In these instances, we had no a priori hypotheses about which tools or precipitation levels would be used most frequently or longer under the different tool conditions. We also used exploratory analyses to look for between subject differences in simulation outcomes for the West and the East sectors (i.e., 1[West] - 1[East]).

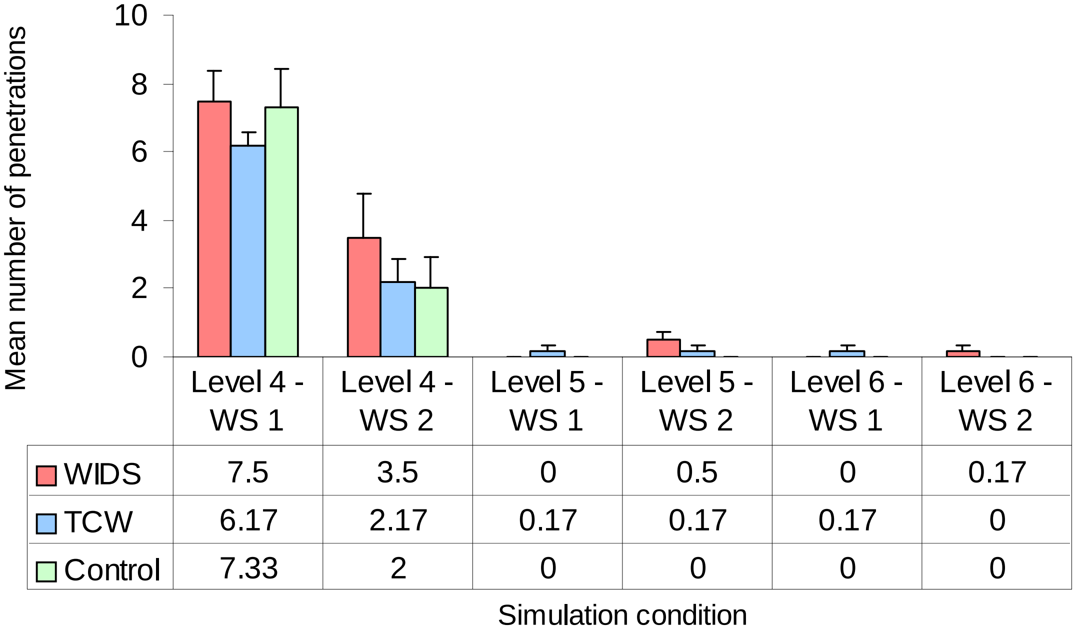
6. Results and Conclusions

6.1 Severe Weather Avoidance

To measure the effect of advanced weather information on severe weather avoidance, we developed a weather proximity index (WPI) that calculated, for every aircraft update, the proximity of each GENERA aircraft to weather Levels 4, 5, and 6. If an aircraft position (x, y) was within the ITWS weather cell polygons (x, y) for Levels 4, 5, and 6, it was classified as a *penetration*. Ideally, the WPI would take several other parameters into account for these calculations. For example, metric information about echo tops, echo bottom, echo height, maximum reflective value, etc., should be used to arrive at a three-dimensional classification that accurately takes weather cell and aircraft altitude into consideration (Rhoda & Pawlak, 1999). However, our prerecorded ITWS data did not contain such detailed, three-dimensional storm cell data. Therefore, our analysis was stricly two-dimensional. The controllers and simulation pilots viewed the same precipitation levels, but neither party had access to detailed altitude information for weather cells. As a result of this limitation, our penetration data in Figure 10 were very conservative and biased; there were too many hits and too few correct rejections recorded. For example, in many instances where aircraft penetrated ‘pop-up’ cells in close proximity to runways (matching x and y positions) and were classified as penetrations, aircraft were not at the altitude for those weather levels and should have been classified as correct rejections. Nevertheless, the WPI index served as a general indicator for controller WSA and allowed us to explore the effect of different scenarios and weather tool presentations.

Our hypothesis that weather tools would enhance controllers’ ability to reduce aircraft weather cell penetrations (λ_p = .5[WIDS] + .5[TCW] -1[Control]) was not confirmed by the data. Figure 10 shows the mean number of weather cell penetrations for WS 1 and WS 2. There were no significant differences in the mean number of penetrations for Levels 4-6 between weather tool conditions (WIDS and TCW) and the Control condition. Overall, there were very few Levels 4-6 penetrations indicating that controllers were successful in avoiding weather cells even in the case when no advanced weather information was available.

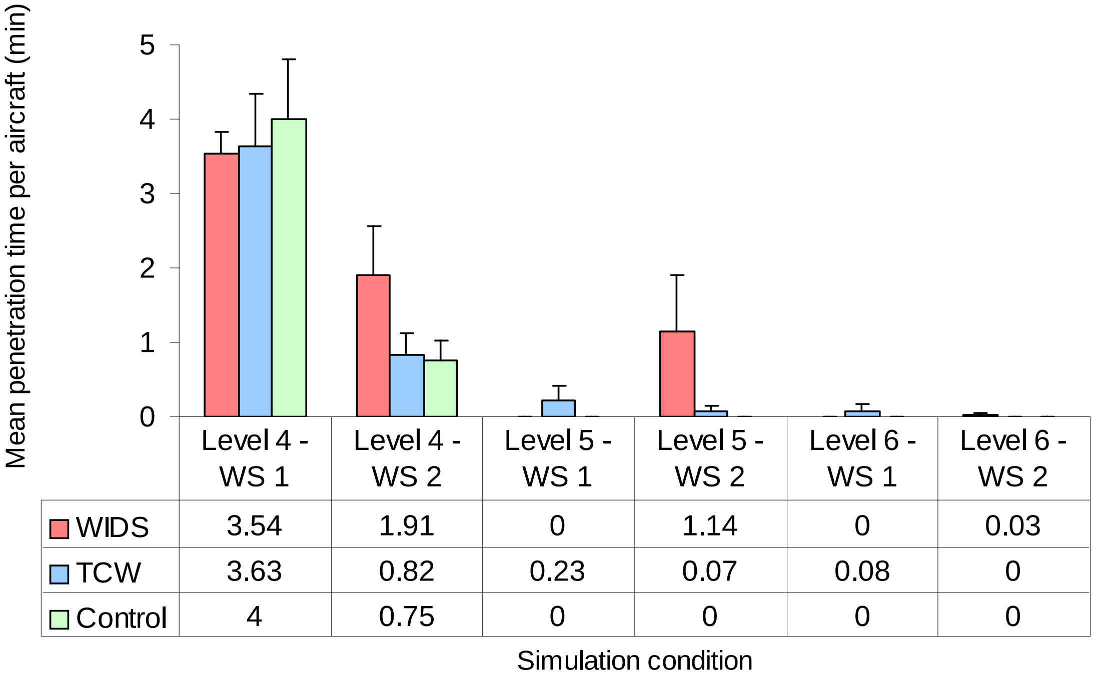
The main reason for the lack of a substantial reduction in penetrations for tool conditions lies in the nature of WS 1 and WS 2. According to SMEs, while controllers actively used weather tools and avoided Levels 4-6 while vectoring aircraft to final approach, they were not able to use the weather information to avoid Levels 4-6 ‘pop-ups’. Therefore, the penetration data in Figure 10 were almost exclusively a result of unexpected ‘pop-ups’ during the scenarios. This is important because the weather tools provide useful information for route planning and runway selection, but it is clear that in the scenarios these tools did not provide the information necessary to avoid storm cell ‘pop-ups’ and storm cell growth.



	Level 4 - WS 1	Level 4 - WS 2	Level 5 - WS 1	Level 5 - WS 2	Level 6 - WS 1	Level 6 - WS 2
🟥 WIDS	7.5	3.5	0	0.5	0	0.17
🟦 TCW	6.17	2.17	0.17	0.17	0.17	0
🟩 Control	7.33	2	0	0	0	0

Figure 10. Mean number of weather cell penetrations by weather levels and simulation condition. The error bars are standard errors (*SE*).

Figure 11 shows the mean penetration times per aircraft for Levels 4-6 by simulation condition and weather scenario. Again, there were no significant differences in mean penetration times for Levels 4-6 between the weather tool conditions (WIDS and TCW) and the Control condition.



	Level 4 - WS 1	Level 4 - WS 2	Level 5 - WS 1	Level 5 - WS 2	Level 6 - WS 1	Level 6 - WS 2
🟥 WIDS	3.54	1.91	0	1.14	0	0.03
🟦 TCW	3.63	0.82	0.23	0.07	0.08	0
🟩 Control	4	0.75	0	0	0	0

Figure 11. Mean penetration time (min) for each aircraft by weather levels and simulation condition. The error bars are *SE*.

6.2 Number of Instrument Operations

This dependent variable is one of the key measures in this study. Instrument operations encompass many things, but in the present context, we concentrate on the aspect of instrument operations that deals with completed flights. As soon as an aircraft has passed the final approach fix, the pilot will contact the tower for a landing clearance. At this point, the aircraft will be under the responsibility of the tower controller. Therefore, the number of instrument operations serves as a de facto measure of completed flights in the simulation.

Figure 12 shows the mean number of instrument operations for the WIDS, TCW, and Control conditions by weather scenario. We found no evidence that weather tools helped controllers to complete more flights during WS 1.

For WS 2, however, there was a significant one-tailed contrast $t(5) = 2.99$, $p = .015$ ($L = 2.75$, 95% CI [.90 to 4.61], $SD = 2.25$, $r_{\text{contrast}} = .80$), showing that controllers performed more instrument operations during the WIDS and TCW conditions compared to the Control condition.

More important than the statistical significance, however, is the fact that this difference is *operationally* significant. On average, controllers completed 34 flights during Control conditions, and increased this number by 2.16 and 3.33 flights when presented with the TCW and WIDS information, respectively. This equates to an increase in instrument operations by 6% and 10%.

We also performed an exploratory analysis to test for differences in the number of instrument operations between the West and East sectors, but found no significant differences.

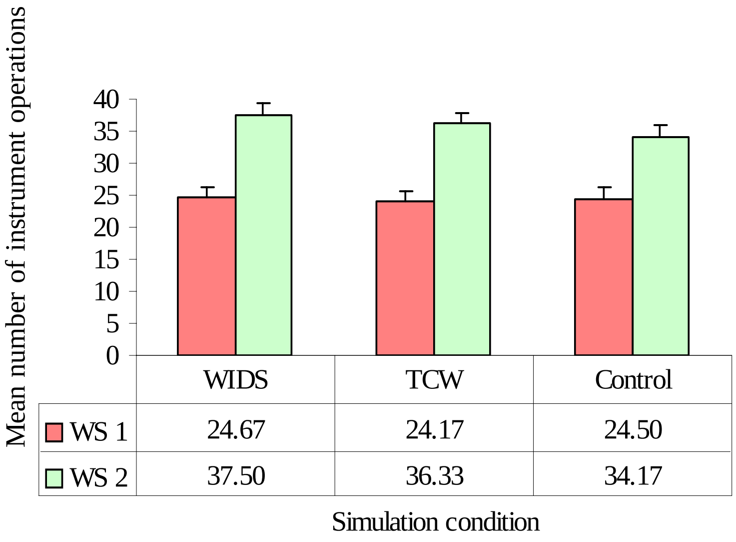


Figure 12. Mean number of instrument operations by weather scenario and simulation condition. The error bars are *SE*.

6.3 Distance Flown

Researchers analyzed both the mean cumulative distance flown and the mean distance flown per aircraft. We found no significant differences between simulation conditions and weather scenarios for either analysis. Figure 13 shows the mean distance flown per aircraft by simulation condition and weather scenario. The mean distance flown per aircraft was similar regardless of simulation condition and weather scenario.

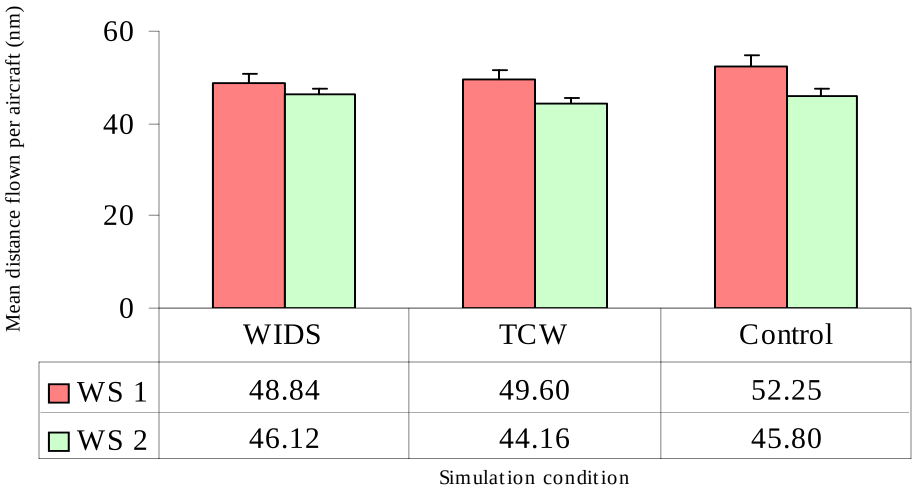


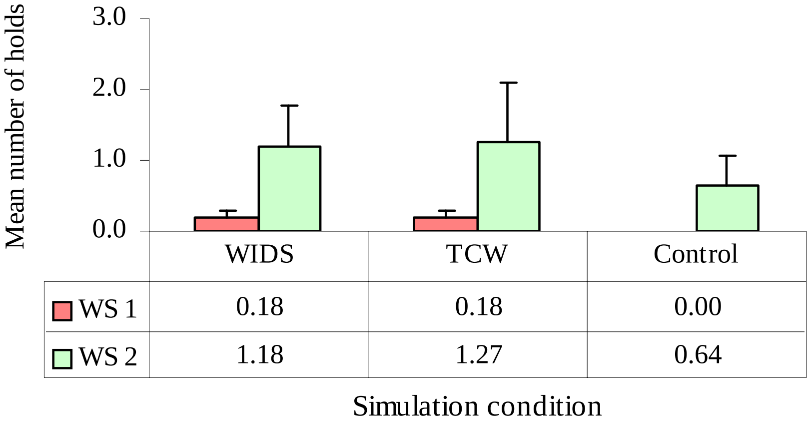
Figure 13. Mean distance flown per aircraft by weather scenario and simulation condition. The error bars are *SE*

6.4 Number of Terminal Holds

Most NAS delays are due to airport saturation or severe weather conditions. During severe weather conditions affecting TRACON operations, controllers often stop arriving aircraft from entering their sector. Instead, aircraft are put on hold outside the TRACON sector until conditions favor new arrivals. In current NAS operations, weather information is not readily accessible to TRACON controllers at their workstations. As a result, there is less information available for controllers to guide their routing and hold decisions. During WIDS and TCW conditions, however, controllers had advanced weather information to aid their routing and hold decisions.

For the present analysis, we assessed if advanced weather information affected the way controllers managed holding patterns. Specifically, we assessed whether the presence of weather tools allowed controllers to perform more holds within the TRACON airspace.

Figure 14 shows the mean number of terminal holds by simulation condition and weather scenario. There were no significant differences between simulation conditions for either WS 1 or WS 2.



	WIDS	TCW	Control
🟥 WS 1	0.18	0.18	0.00
🟩 WS 2	1.18	1.27	0.64

Figure 14. Mean number of terminal holds by weather scenario and simulation condition. The error bars are *SE*.

6.5 Duration of Holds

Researchers also computed the mean duration of holds from the data in Figure 14. Figure 15 shows the mean duration of terminal holds per aircraft by simulation condition and weather scenario. There was a significant one-tailed contrast for WS 2 $t(10) = 1.96$, $p = .039$ ($L = 1.27$, 95% *CI* [.10 to 2.46], $SD = 2.15$, $r_{\text{contrast}} = .53$), showing that mean hold durations within the TRACON airspace were longer for each aircraft during WS 2 for WIDS and TCW conditions compared to the Control condition.

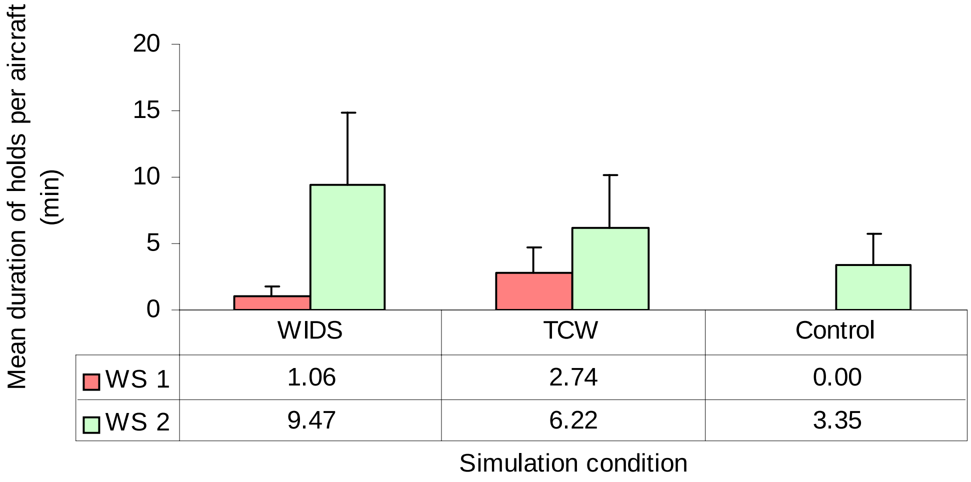


Figure 15. Mean duration of terminal holds per aircraft by weather scenario and simulation condition. The error bars are SE.

6.6 Number of Altitude Commands

For the analysis of altitude commands, we analyzed both the mean number of altitude commands and the mean number of altitude commands per aircraft. We found no significant differences between simulation conditions and weather scenarios for either analysis. Figure 16 shows the mean number of altitude commands per aircraft by simulation condition and weather scenario. The mean number of altitude commands was similar across conditions, reflecting a similar use of altitude commands by controllers regardless of simulation condition and weather scenario.

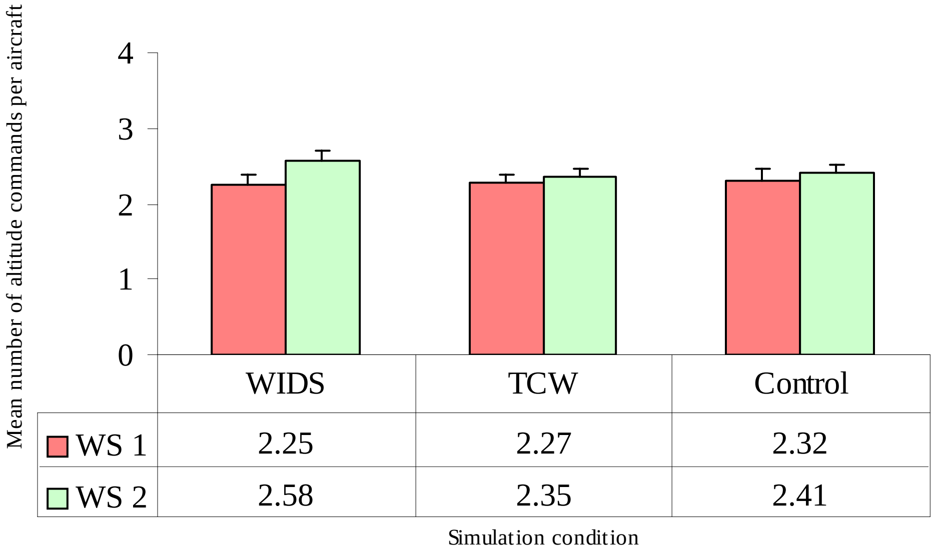


Figure 16. Mean number of altitude commands per aircraft by weather scenario and simulation condition. The error bars are *SE*

6.7 Number of Heading Commands

For the analysis of heading commands, we analyzed both the mean number of heading commands and the mean number of heading commands per aircraft. We found no significant differences between weather tool conditions and the Control condition and weather scenarios for either analysis. Figure 17 shows the mean number of heading commands per aircraft by simulation condition and weather scenario. A comparison between weather tool conditions (1[WIDS] – 1[TCW]) for WS 2 revealed a significant two-tailed contrast $t(10) = 4.20$, $p = .002$ ($L = .40$, 95% *CI* [.19 to .61], $r_{\text{contrast}} = .80$), indicating that controllers performed significantly more heading commands during the WIDS condition compared to the TCW condition.

A factor that could have contributed to more heading commands in the WIDS condition was the spatial separation of weather and traffic data during WIDS operations. Although the heading command data are insufficient for a definitive conclusion, the increased number of heading commands for WIDS conditions could nevertheless be due to this separation. During TCW conditions, controllers had immediate access to both weather tools and traffic data in one spatial location. During WIDS conditions, controllers had to look up at the WIDS display when using weather tools and look down on the situation display when observing traffic data. This spatial separation could potentially have contributed to a detrimental temporal delay that manifested itself in more corrective heading commands by controllers.

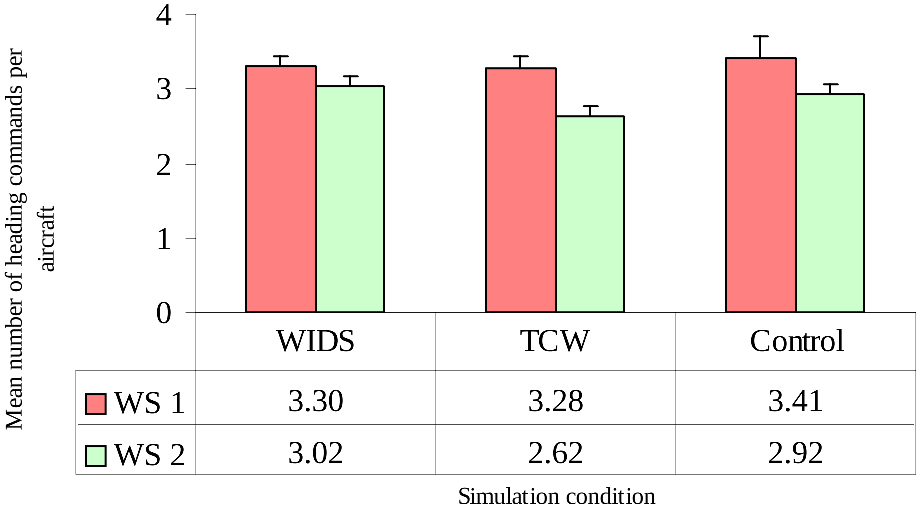


Figure 17. Mean number of heading commands per aircraft by weather scenario and simulation condition. The error bars are *SE*.

6.8 Number of Speed Commands

For the analysis of speed commands, we analyzed both the mean number of speed commands and the mean number of speed commands per aircraft. We found no significant differences between simulation conditions and weather scenarios for either analysis. Figure 18 shows the mean number of speed commands per aircraft by simulation condition and weather scenario. The mean number of speed commands was similar across conditions, reflecting a similar use of speed commands by controllers regardless of simulation condition and weather scenario.

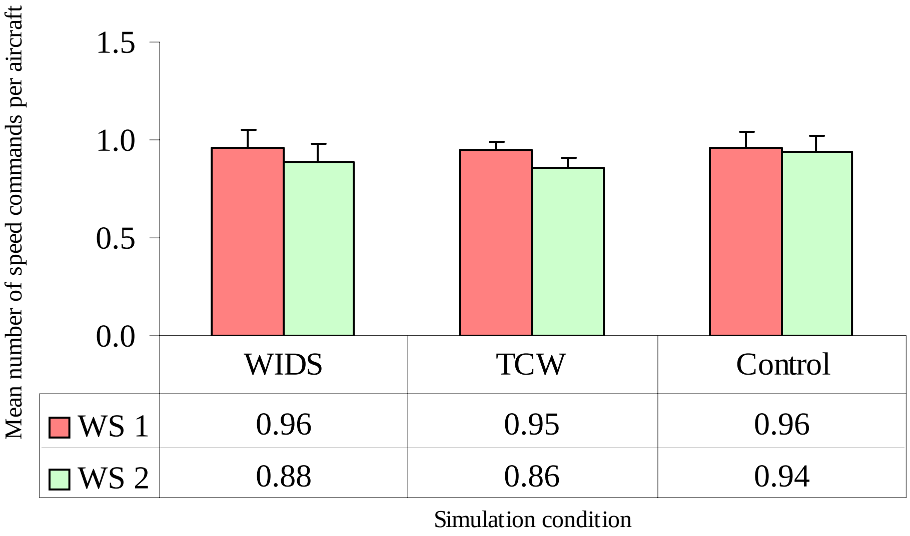


Figure 18. Mean number of speed commands per aircraft by weather scenario and simulation condition. The error bars are *SE*.

6.9 Number of Handoffs

Figure 19 shows the mean number of handoffs by simulation condition and weather scenario. There was a significant one-tailed contrast $t(10) = 2.75$, $p = .010$, ($L = 1.68$, 95% CI [.57 to 2.79], $SD = 2.03$, $r_{\text{contrast}} = .66$) for WS 2, indicating that significantly more handoffs occurred during WIDS and TCW conditions compared to the Control condition. A likely explanation for the increased number of handoffs for WIDS and TCW conditions is the fact that controllers handled more aircraft during these conditions.

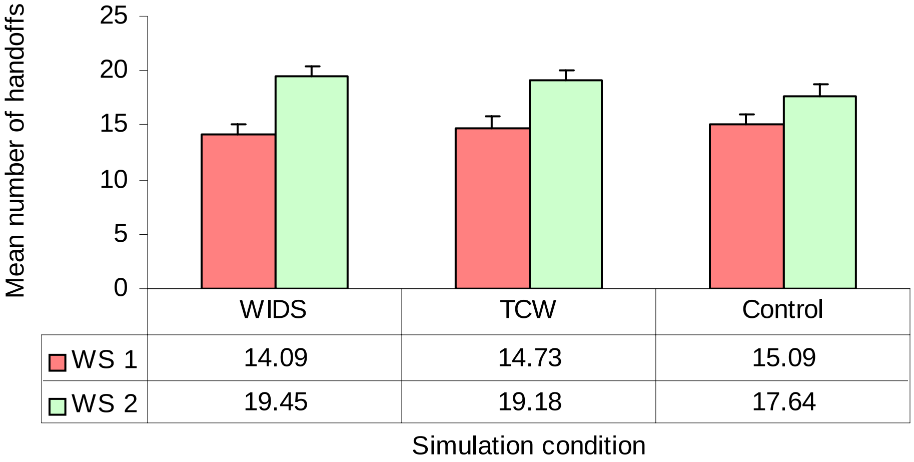
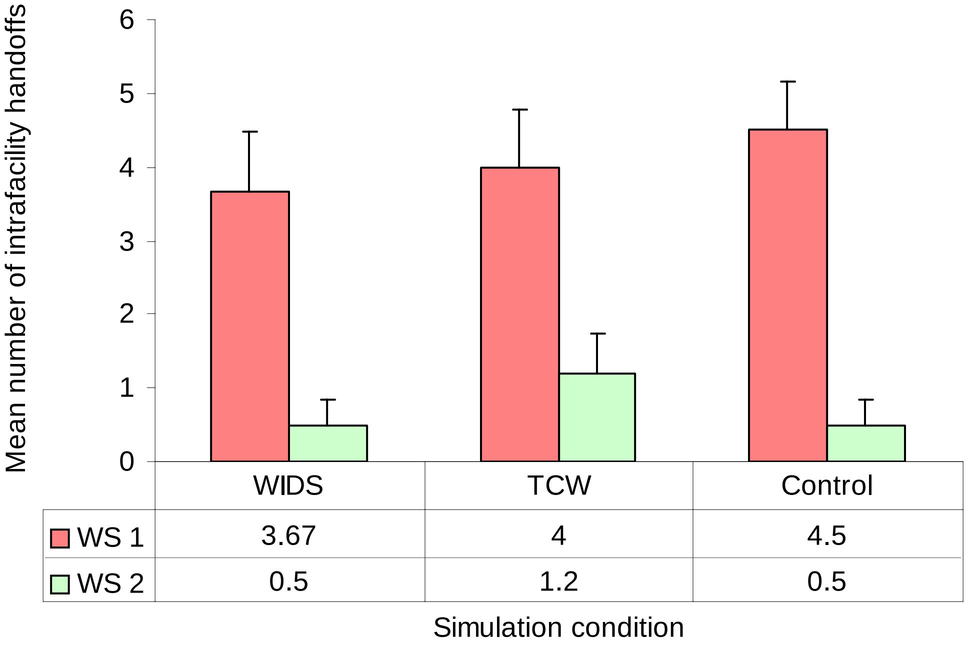


Figure 19. Mean number of handoffs by weather scenario and simulation condition. The error bars are *SE*.

Although the result in Figure 19 shows an increase in the total number of handoffs during WIDS and TCW conditions, we also analyzed the data for intrafacility handoffs (between the GENERA

East and West controller) to assess whether the presence of weather tools increased the handoffs between controllers. Figure 20 shows the mean number of intrafacility handoffs. Few intrafacility handoffs were used, and they occurred almost exclusively during WS 1.



	WIDS	TCW	Control
🟥 WS 1	3.67	4	4.5
🟩 WS 2	0.5	1.2	0.5

Figure 20. Mean number of intrafacility handoffs by simulation condition and weather scenario. The error bars are *SE*.

6.10 Loss of Separation

During the scenarios, the controllers had to maintain the minimum of 1000 ft vertical or 3 miles lateral separation until established on their respective final approach course. Based on our TGF system measures for aircraft separation, the SMEs determined that only three separation violations had occurred during the simulation. One controller, who did not comply with the specified minimum separation, committed all three separation errors. One violation occurred in a WIDS condition during WS 1, and two additional violations occurred in the same WIDS condition during WS 2.

6.11 Wake Turbulence Violations

There were no recorded wake turbulence violations during the simulation.

6.12 Push-To-Talk Communications

For the analysis of communications, we analyzed both the mean number of communications and the mean number of communications per aircraft. We found no significant differences between simulation conditions and weather scenarios for either analysis. We also performed an exploratory analysis to test for differences in the number of communications between the West and East sectors, but found no significant differences. Figure 21 shows the mean number of controller communications per aircraft by weather scenario and simulation condition. The mean number of communications was similar across conditions regardless of simulation condition and weather scenario.

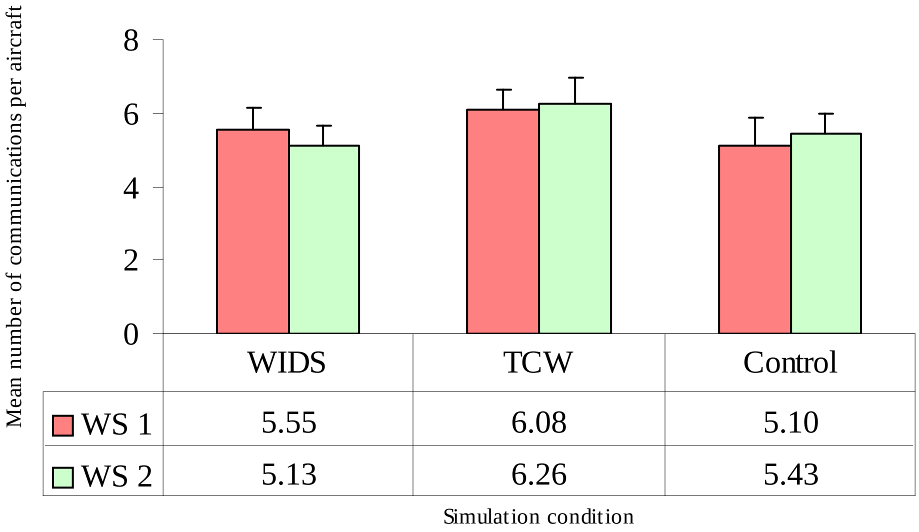


Figure 21. Mean number of communications per aircraft by weather scenario and simulation condition. The error bars are *SE*.

Figure 22 shows the mean controller communication time per communication by simulation condition and weather scenario. There was a significant two-tailed contrast for WS 2 $t(10) = -2.32$, $p = .043$ ($L = -.22$, 95% *CI* [-.44 to -.01]), $SD = .32$, $r_{\text{contrast}} = .59$, indicating that communications were longer for the Control condition compared to the WIDS and TCW conditions. This was expected because controllers broadcast SIGMETS (Appendices A and B) from printed paper strips during the Control condition and also requested more pilot reports. Our analysis of the durations for pilot communications (Figure 23) also showed a significant two-tailed contrast for WS 2 $t(29) = -2.53$, $p = .017$ ($L = -.12$, 95% *CI* [-.21 to -.02]), $SD = .25$, $r_{\text{contrast}} = .42$, indicating the same trend of longer communication durations for pilots during the Control condition.

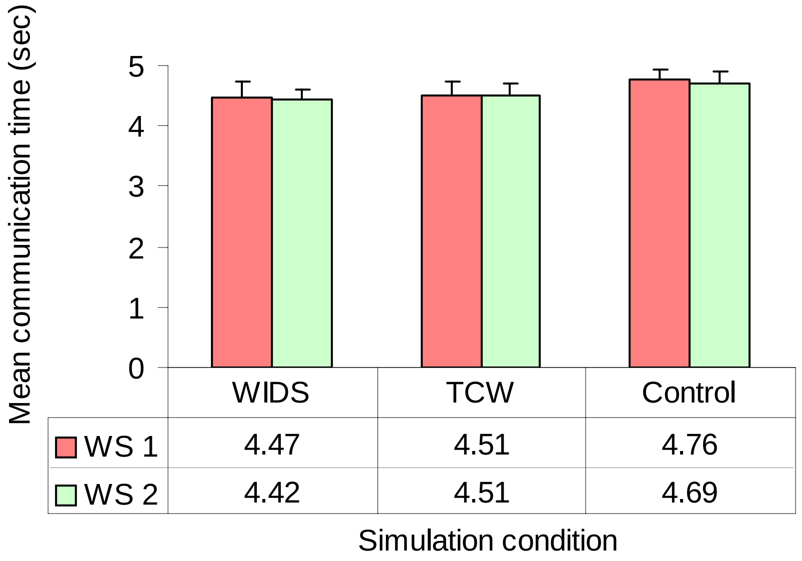


Figure 22. Mean controller communication time (sec) per communication by weather scenario and simulation condition. The error bars are *SE*.

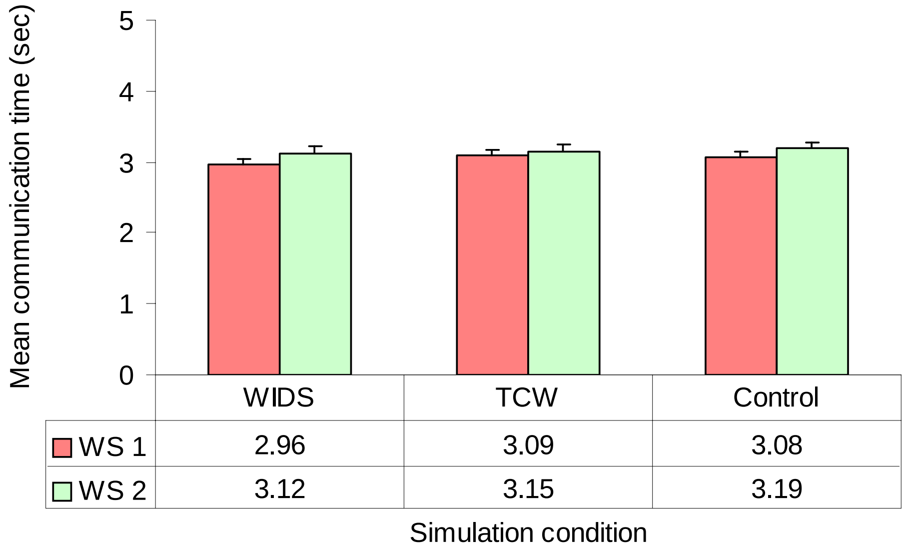
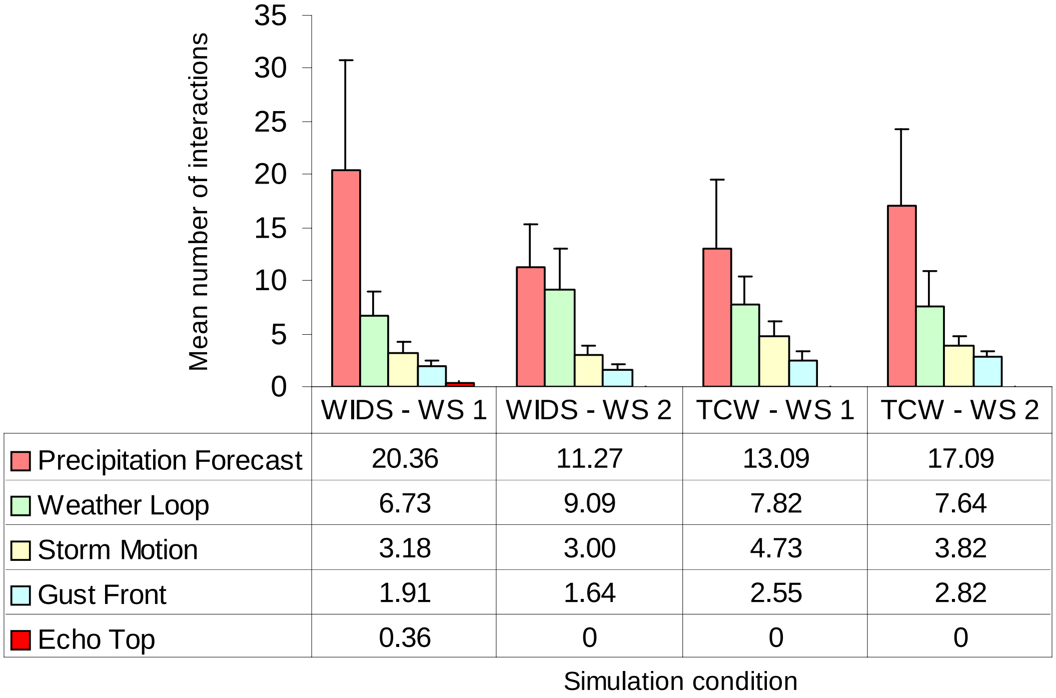


Figure 23. Mean pilot communication time (sec) per communication by weather scenario and simulation condition. The error bars are *SE*.

6.13 Weather Tool Interactions

In the following section, we present an analysis of weather tool interactions for the WIDS and TCW conditions. During the simulation, every controller interaction with weather tool menus on the WIDS and TCW were recorded and time-stamped. We could therefore analyze how often controllers activated each weather tool. Figure 24 shows the mean number of weather tool interactions by simulation condition and weather scenario. The highest number of interactions for all simulation conditions occurred for the Precipitation Forecast and the Weather Loop tools.

In fact, the combined number of interactions for these two weather tools accounted for 74-83 percent of all weather tool interactions for the simulation conditions. The interaction frequencies for the Storm Motion, Gust Front, and Echo Top tools, were much lower, ranging from 10% to 17% for Storm Motion and 6% to 9% for Gust Front. For Echo Top, there was only one frequency of 1% for the WIDS condition during WS 1. We conducted exploratory analyses using two-tailed contrasts on the mean number and duration of interactions per weather tool, but for the Precipitation Forecast, Weather Loop, Storm Motion, and Echo Top tools, we did not find any significant differences between simulation conditions and weather scenarios. However, for the Gust Front tool there was a significant two-tailed contrast (1[WIDS] – 1[TCW]) $t(10) = -2.67$, $p = .024$ ($L = -1.18$, 95% *CI* [-2.17 to -.19], $r_{\text{contrast}} = .644$) indicating a larger number of controller interactions with the Gust Front tool during the TCW conditions ($M = 2.82$) compared to the WIDS conditions ($M = 1.64$). We also performed an exploratory analysis to test for differences in tool usage between the West and the East sectors, but found no significant differences.

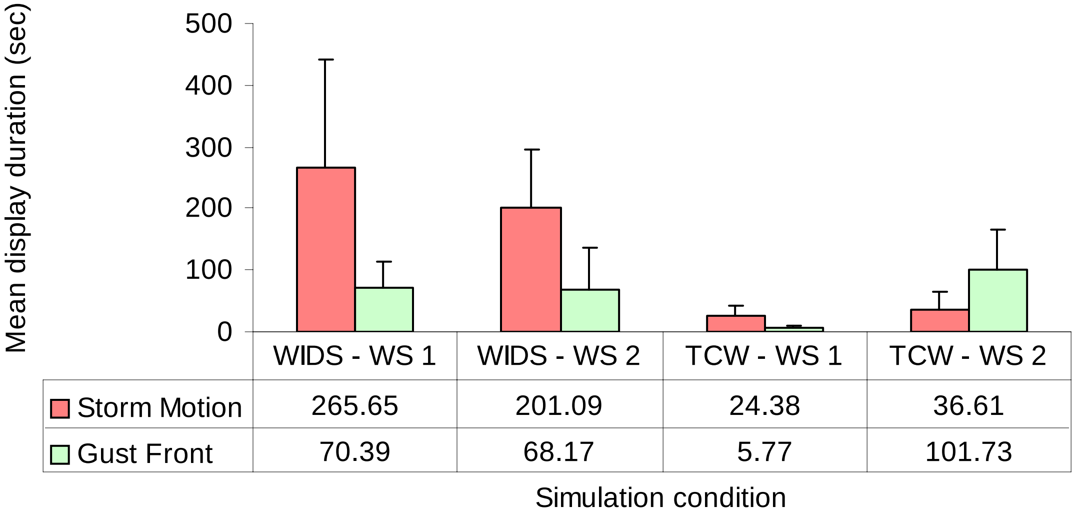


	WIDS - WS 1	WIDS - WS 2	TCW - WS 1	TCW - WS 2
🟥 Precipitation Forecast	20.36	11.27	13.09	17.09
🟩 Weather Loop	6.73	9.09	7.82	7.64
🟨 Storm Motion	3.18	3.00	4.73	3.82
🟦 Gust Front	1.91	1.64	2.55	2.82
🟥 Echo Top	0.36	0	0	0

Figure 24. Mean number of interactions for weather tools during the WIDS and TCW conditions by weather scenario. The error bars are *SE*.

Although Figure 24 presents the interaction frequencies for weather tools, we must consider one aspect of the data before making conclusions about the relative importance of these tools. There was a confound between the number of times a tool was used, the total duration of usage, and the ability to display more than one tool simultaneously. In the prototypes used for this simulation, the Storm Motion and Gust Front tools had no default display duration; they could be displayed for the entire scenario. Furthermore, the Gust Front and the Storm Motion tools could be displayed simultaneously with other weather tools. On the other hand, the Precipitation Forecast and the Weather Loop tools both had default display durations and could not be displayed simultaneously with other tools. Upon activation, the Precipitation Forecast was displayed for two seconds, while the Weather Loop continued to run for 30 seconds unless interrupted. To interpret the frequencies in Figure 24 accurately, we need to separately assess the mean display durations for the Gust Front and Storm Motion tools. For this analysis, we excluded the data from the four controllers who had the Gust Front and Storm Motion tools activated during the entire scenario. The remaining eight controllers had an entirely different pattern of display durations.

Figure 25 presents the mean display duration per activation for the Gust Front and Storm Motion tools by weather scenario. As can be seen in Figure 25, the mean display duration for the Storm Motion and Gust Front tools varies greatly across simulation conditions and weather scenarios. However, because of the large spread in the data, none of these differences were statistically significant.



	WIDS - WS 1	WIDS - WS 2	TCW - WS 1	TCW - WS 2
🟥 Storm Motion	265.65	201.09	24.38	36.61
🟩 Gust Front	70.39	68.17	5.77	101.73

Figure 25. Mean display duration (sec) for Gust Front and Storm Motion tools by simulation condition and weather scenario. The figure excludes data from one controller that displayed Gust Front for the entire scenario (50 min). Similarly, we also excluded three controllers that displayed Storm Motion for the entire scenario. The error bars are *SE*.

However, display frequencies and display durations do not tell the whole story with regard to information retrieval from weather tools. If the weather tools had relatively long activation durations on the WIDS and TCW, it did not necessarily mean that controllers actively focused their attention on these display objects. Furthermore, in the case of the display of Microburst and Wind Shear objects, where controllers lacked the ability to turn display objects on and off, we needed to assess how often and for how long controllers directed their attention to these display objects. To assess how controllers' display of Gust Front, Microburst, Storm Motion, and Wind Shear objects related to their focal attention, we used the West controllers' point-of-gaze (POG) data from oculometer recordings to calculate the number and duration of fixations (see Appendix F). Table 3 shows the mean number of recorded fixations for the Gust Front, Microburst, Storm

Motion, and Wind Shear objects, and Table 4 shows the corresponding mean fixation durations. There were few fixations on all weather objects, regardless of weather scenario and display condition. For the WIDS condition in WS 2, we had no recorded fixations for the Gust Front, Microburst, or Storm Motion objects. Similarly, for the TCW condition in WS 2, there were no recorded fixations for Microburst. This makes sense because WS 2 only contained one Microburst that was displayed at the end of the scenario. It is somewhat more difficult to account for the lack of fixations on the Gust Front and Storm Motion objects because controllers used these tools during WS 2. Furthermore, we were unable to record fixations from all six controllers. In fact, for 64% of all recorded fixations in Table 3, the data points come from one single West side controller.

The corresponding fixation durations were also relatively short in most cases, indicating that controllers did not focus much direct attention on these objects. Two exceptions were the fixation durations for the Wind Shear object in the TCW condition. At an average of 520.5 (WS 1) and 407.8 msec (WS 2), the fixations were relatively long for a simple display object like the Wind Shear symbol. For the shorter fixation durations for the Gust Front and Storm Motion objects, we hypothesize that controllers mainly paid attention to the 10 and 20 min extrapolated positions. Because the perception of the location of solid and dotted lines did not require much visual processing, it was possible that controllers perceived these lines without direct focal attention. On the other hand, extracting the wind speed numbers would require direct focal attention, and if controllers did this during simulation runs, we would expect to see much longer fixation durations for the Gust Front and Storm Motion objects.

Table 3. Mean Number of Fixations for the Gust Front, Microburst, Storm Motion and Wind Shear Objects by Weather Scenario and Display Condition

(Numbers within parenthesis are SE and n is the number of participants who fixated an object at least once.)

	WS 1		**WS 2**	
	WIDS	**TCW**	**WIDS**	**TCW**
Gust Front	3 (NA) *n* = 1	0	0	36 (NA) *n* = 1
Microburst	4 (NA) *n* = 1	6 (NA) *n* = 1	0	0
Storm Motion	100 (NA) *n* = 1	4.7 (2.3) *n* = 3	0	4.3 (2.3) *n* = 4
Wind Shear	1 (NA) *n* = 1	4.3 (2.9) *n* = 4	3 (NA) *n* = 1	2.4 (1.0) *n* = 5

Table 4. Mean Fixation Durations (msec) for the Gust Front, Microburst, Storm Motion and Wind Shear Objects by Weather Scenario and Display Condition

(Numbers within parenthesis are SE and n is the number of participants who fixated an object at least once.)

	WS 1		WS 2	
	WIDS	**TCW**	**WIDS**	**TCW**
Gust Front	388.9 (NA) *n* = 1	0	0	327.3 (NA) *n* = 1
Microburst	220.9 (NA) *n* = 1	277.8 (NA) *n* = 1	0	0
Storm Motion	326.3 (NA) *n* = 1	226.5 (15.8) *n* = 3	0	300.5 (45.4) *n* = 4
Wind Shear	183.3 (NA) *n* = 1	520.5 (239.1) *n* = 4	138.9 (NA) *n* = 1	407.8 (140.4) *n* = 5

In summary, the controllers interacted less with the Gust Front and Storm Motion tools compared to the Precipitation Forecast and Weather Loop tools. The controllers also displayed the Gust Front and Storm Motion tools for relatively short durations. During these relatively short display durations, the controllers seem to pay little direct focal attention to these weather objects. For the Microburst and Gust Front information, we found very few fixation recordings and relatively short fixation durations, and the majority of recordings come from one controller. Only in the case of fixation recordings for Storm Motion and Wind Shear objects for the TCW condition do we have recorded fixations from more than one controller.

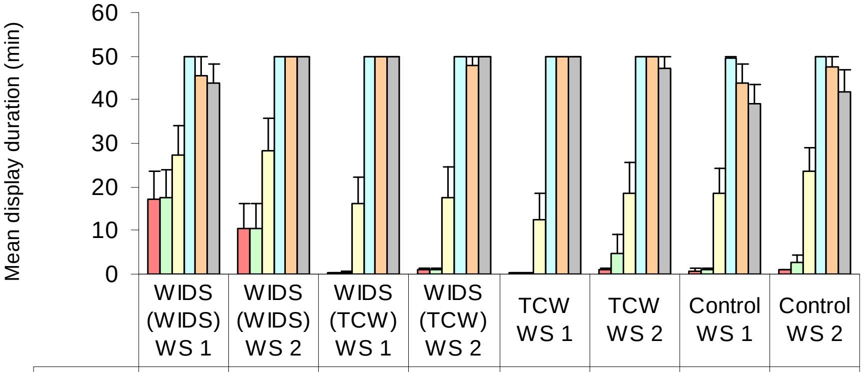
The result of the present weather tool interaction analysis also points to an important human factors consideration. Because of the high frequency of use for the Precipitation Forecast and the Weather Loop tools, these tools must be easily accessible to prevent diversion of attention from the situation display. During the present simulation, we used toolbar activation for all weather tools. From a simulation perspective, this had the advantage of not requiring controllers to use unfamiliar key combinations. From a human factors perspective, however, it may have reduced the interaction frequency for most weather tools, particularly the Precipitation Forecast and Weather Loop tools. During simulation debriefings, controllers frequently complained that weather tool interactions should not be initiated from a toolbar. The controllers felt that providing quick-keys or specialized auxiliary keypads would increase weather tool use and alleviate the need to shift attention away from traffic data.

The shift in attention away from traffic data could also be a potential problem during WIDS conditions. Controllers could have spent a large amount of the total simulation time looking at the WIDS display (i.e., ‘heads-up’ time). However, using POG data from the oculometer recordings, we found that controllers only had an average total viewing time of 1.61 min (*SE* = .56) on the auxiliary WIDS display during WS 1, and an average total viewing time of 4.52 min (*SE* = 1.86) during WS 2.

6.14 Precipitation Display Interactions

In the following data presentation, we analyzed how controllers used precipitation levels during the simulation. Due to the dual display configuration during WIDS conditions, there were four possible display configurations for precipitation levels. For WIDS conditions, the display condition WIDS (TCW) refers to the precipitation levels displayed on the main TCW display, whereas the WIDS (WIDS) display condition refers to the precipitation levels displayed on the auxiliary WIDS display during WIDS conditions.

Because we had no a priori expectation for differences in precipitation display use, we conducted three exploratory analyses using two-tailed post-hoc contrasts (1[WIDS/WIDS] – 1[Control], 1[WIDS/TCW] – 1[Control], and 1[TCW] – 1[Control]) on the mean number of interactions and the mean display duration. We found no significant differences between these conditions. Figure 26 shows the mean display duration for Levels 1-6 by weather scenario for the WIDS (WIDS), WIDS (TCW), TCW, and Control conditions, respectively.



	WIDS (WIDS) WS 1	WIDS (WIDS) WS 2	WIDS (TCW) WS 1	WIDS (TCW) WS 2	TCW WS 1	TCW WS 2	Control WS 1	Control WS 2
🟥 Level 1	17.16	10.29	0.39	0.88	0.22	0.86	0.80	0.85
🟩 Level 2	17.36	10.30	0.45	0.90	0.23	4.70	0.88	2.78
🟨 Level 3	27.26	28.32	16.16	17.54	12.62	18.58	18.61	23.67
🟦 Level 4	50.00	50.00	49.74	50.00	49.94	50.00	49.49	49.96
🟧 Level 5	45.54	50.00	50.00	47.74	50.00	50.00	43.82	47.69
⬜ Level 6	43.71	50.00	50.00	50.00	49.79	47.04	39.11	41.75

Figure 26. Mean display duration of Levels 1-6 by display condition and weather scenario. The error bars are *SE*.

In Figure 26 we present the mean display duration for Levels 1-6 by display condition and weather scenario. As can be seen in the figure, the controllers displayed Levels 4-6 longer than Levels 1-3. This is not surprising because controllers were responsible for keeping aircraft away from Levels 4-6. Furthermore, displaying Levels 1-6 at all times during scenarios would have added a large degree of visual noise and clutter. It is only when precipitation was presented on the WIDS auxiliary display that controllers displayed Levels 1 and 2 for longer durations. In this instance, there were no traffic data superimposed on the precipitation levels, and therefore, less concern for visual noise and clutter.

To assess how controllers' display of precipitation levels related to their focal attention, we again used the West controllers' POG data to calculate the number and duration of fixations for each weather level. Table 5 shows the mean number of recorded fixations for Levels 1-6, and Table 6 shows the corresponding mean fixation durations. The majority of fixations were on Levels 3-6, with fewer fixations on Levels 1, 2, and 6. This pattern corresponds to the interaction data in that controllers mostly used Levels 3-6 during simulation runs. There were few recorded fixations for Level 6, most likely because Level 6, in contrast to Levels 1-5, was not present at all times during WS 1 and WS 2.

The fixation durations for the precipitation levels (see Table 6) were much longer than the fixation durations for the Gust Front and the Storm Motion objects (see Table 4). Here, there were no fixation durations under 200 msec, indicating that controllers directed more focal attention to weather levels during simulation runs. The relatively long durations for Levels 4-6 seem to indicate greater attention to these levels. This makes sense because controllers were responsible for keeping aircraft away from these levels.

Table 5. Mean Number of Fixations for Precipitation Levels by Weather Scenario and Display Condition

(Numbers within parenthesis are *SE* and *n* is the number of participants who fixated a precipitation level at least once.)

	WS 1			**WS 2**		
	WIDS	**TCW**	**Control**	**WIDS**	**TCW**	**Control**
Level 1	0	2.0 (NA) $n = 1$	23.0 (16.0) $n = 3$	71.0 (NA) $n = 1$	20.0 (NA) $n = 1$	6.0 (NA) $n = 1$
Level 2	0	2.0 (NA) $n = 1$	56.3 (37.8) $n = 3$	31.7 (27.7) $n = 3$	0	144.0 (109.0) $n = 2$
Level 3	219.3 (43.4) $n = 3$	234.0 (131.4) $n = 4$	104.6 (76.4) $n = 5$	112.8 (74.3) $n = 4$	374.5 (109.5) $n = 2$	236.0 (176.7) $n = 3$
Level 4	254.2 (45.4) $n = 5$	301.8 (24.4) $n = 5$	200.6 (42.1) $n = 5$	246.3 (44.4) $n = 6$	272.0 (29.6) $n = 5$	280.0 (71.2) $n = 4$
Level 5	162.8 (36.9) $n = 5$	181.4 (27.0) $n = 5$	110.0 (35.3) $n = 5$	101.5 (22.8) $n = 6$	165.4 (16.3) $n = 5$	165.0 (44.3) $n = 4$
Level 6	8.5 (3.3) $n = 4$	5.8 (1.0) $n = 5$	5.0 (NA) $n = 1$	5.2 (1.5) $n = 5$	7.4 (2.4) $n = 5$	3.3 (1.3) $n = 3$

Table 6. Mean Fixation Duration (msec) for Precipitation Levels by Weather Scenario and Display Condition. Numbers within parenthesis are *SE* and *n* is the number of participants who fixated a precipitation level at least once.

	WS 1			**WS 2**		
	WIDS	**TCW**	**Control**	**WIDS**	**TCW**	**Control**
Level 1	0	333.4 (NA) *n* = 1	413.2 (43.8) *n* = 3	697.9 (NA) *n* = 1	452.4 (NA) *n* = 1	386.1 (NA) *n* = 1
Level 2	0	433.4 (NA) *n* = 1	429.1 (20.3) *n* = 3	401.2 (93.0) *n* = 3	0	400.2 (13.1) *n* = 2
Level 3	528.0 (56.6) *n* = 3	437.2 (79.3) *n* = 4	404.1 (37.9) *n* = 5	345.8 (87.7) *n* = 4	507.6 (62.2) *n* = 2	422.7 (21.5) *n* = 3
Level 4	498.2 (40.6) *n* = 5	476.8 (33.7) *n* = 5	461.0 (40.3) *n* = 5	439.3 (43.8) *n* = 6	518.5 (25.8) *n* = 5	446.4 (37.8) *n* = 4
Level 5	485.3 (37.2) *n* = 5	439.7 (25.1) *n* = 5	441.8 (65.7) *n* = 5	396.9 (34.1) *n* = 6	485.1 (39.6) *n* = 5	432.7 (33.4) *n* = 4
Level 6	700.2 (304.3) *n* = 4	363.2 (56.7) *n* = 5	523.3 (NA) *n* = 1	448.0 (131.7) *n* = 5	301.9 (62.1) *n* = 5	243.5 (26.1) *n* = 3

6.15 Examples of Controller Weather Tool Interactions

In the following section, we provide two examples of controller weather tool interactions for the WIDS and TCW conditions. Controllers exhibited large variations in their use of advanced weather tools. In general, controllers had similar patterns of usage with regard to precipitation Levels 1-6. However, there were marked differences in their usage of Echo Top, Precipitation Forecast, Weather Loop, Storm Motion, and Gust Front tools. We illustrate this by showing two representative samples from the interaction data, a ‘high-frequency’ user, and a ‘low-frequency’ user. Figures 27a and 27b illustrate examples of a ‘high-frequency’ user for the WIDS and TCW conditions, respectively. In the figures, we have plotted the display duration (blue bars) of weather tools and precipitation levels as a function of simulation time. As can be seen in the figures, the ‘high-frequency’ user interacted frequently with weather tools, especially the Precipitation Forecast and the Weather Loop tools.

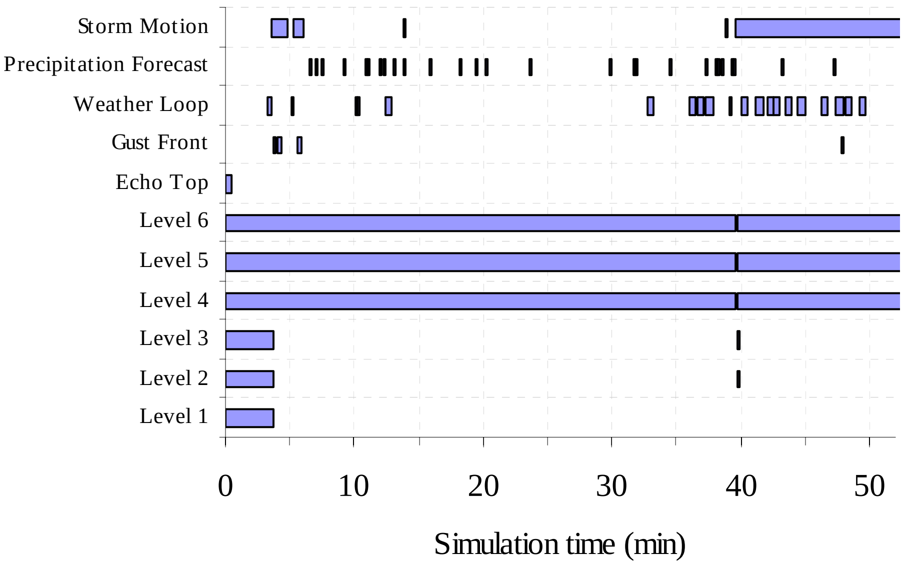


Figure 27a. Illustration of a ‘high-frequency’ user during the WIDS condition.

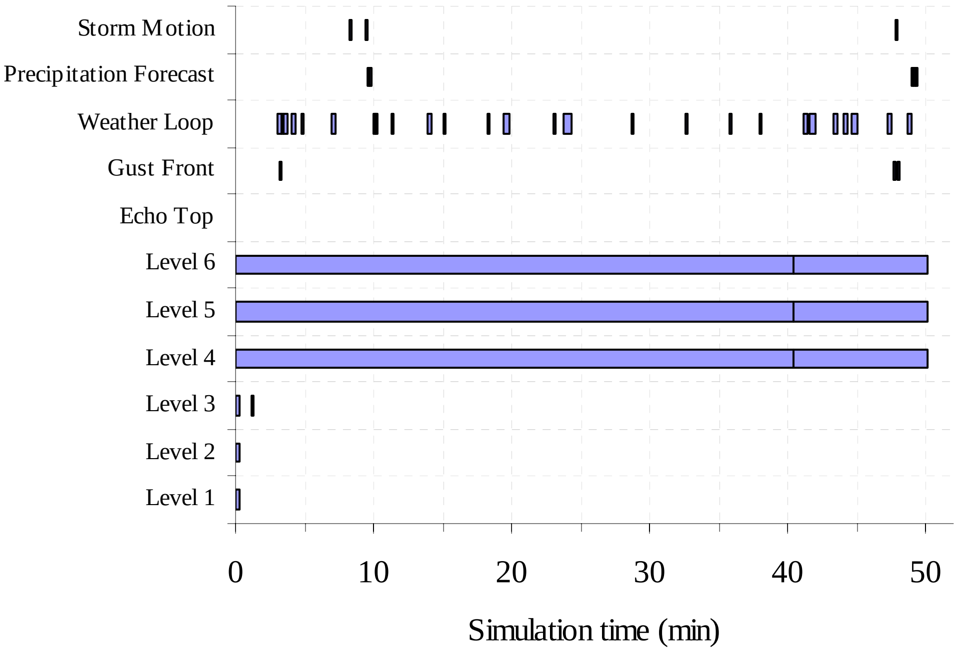


Figure 27b. Illustration of a ‘high-frequency’ user during the TCW condition.

Figures 28a and 28b illustrate interaction data from a ‘low-frequency’ user. The ‘low-frequency’ user displayed very little interaction with weather tools in comparison to the ‘high-frequency’ user.

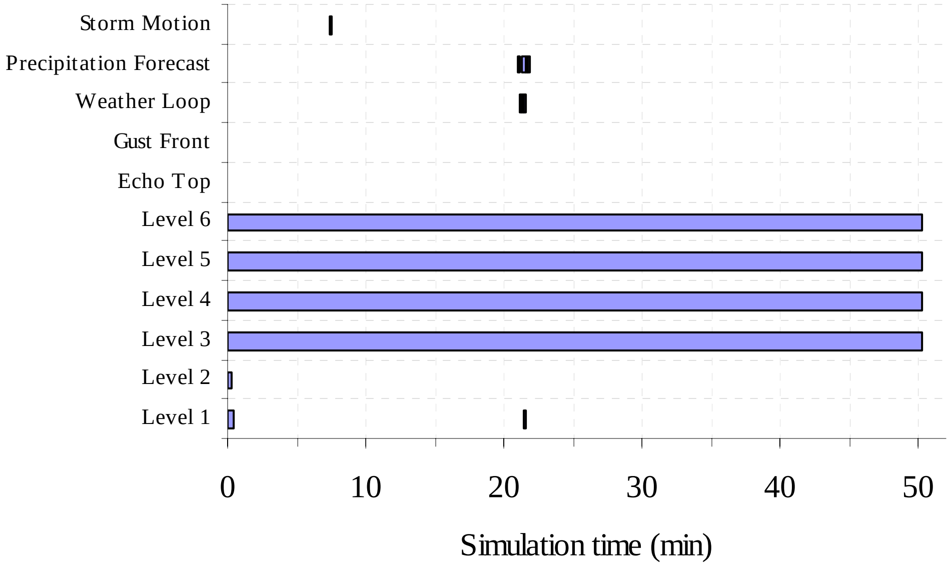


Figure 28a. Illustration of a ‘low-frequency’ user during the WIDS condition.

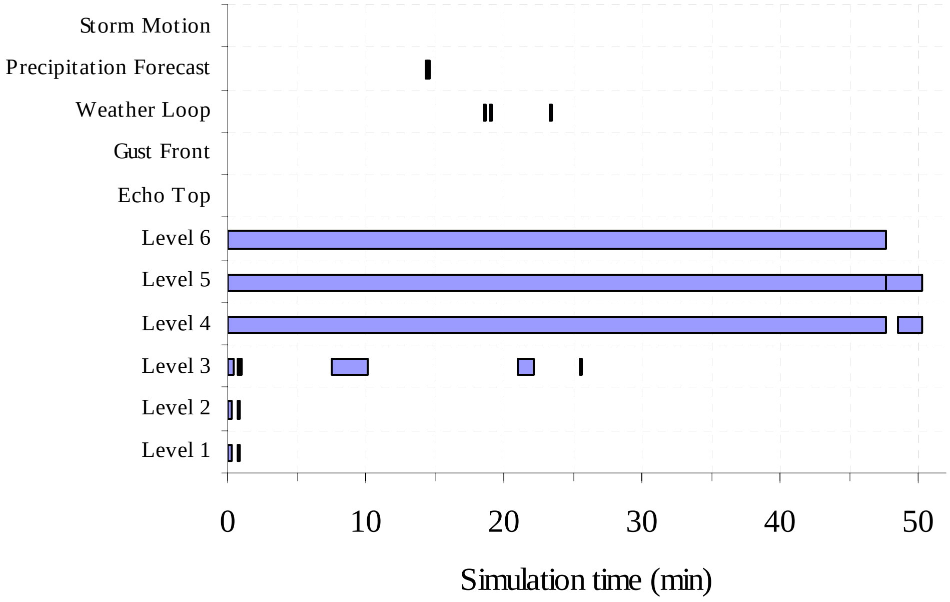


Figure 28b. Illustration of a ‘low-frequency’ user during the TCW condition.

Because of the large individual differences in the frequency of weather tool interactions, we were interested to see if the frequency of tool interactions was positively correlated with dependent measures for our sector throughput variable. To explore this question, we assessed how the frequency of tool interactions correlated with the number of instrument operations (i.e., completed flights). For each group of controllers, we correlated the number of instrument operations in the WIDS and TCW conditions with the total number of tool interactions (i.e., Gust Front, Storm Motion, Precipitation Forecast, and Weather Loop; Echo Top interactions were excluded because there were too few interactions). For this analysis, we used data from both WS1 and WS2 to assess whether controller efficiency improved (i.e. an increase in instrument operations) with increased weather tool interaction.

Most weather tool interactions were between 19 and 83 per condition. However, there were three conditions where interactions were between 116 and 187. We assume these were outliers, probably reflecting tool experimentation by the controllers rather than operational use to facilitate control operations. Figure 29 shows the data points and the best fitting regression line with (solid) and without (dotted) outliers. The slope of the solid line is approximately zero, indicating a nonsignificant correlation between the number of weather tool interactions and the number of instrument operations. However, the dotted regression line shows a significant correlation between the number of tool interactions and the number of instrument operations, *F(*1, 19) = 5.60, *p* = .03, *r* = .48. As the number of weather tool interactions increased, there was also a corresponding increase in the number of instrument operations.

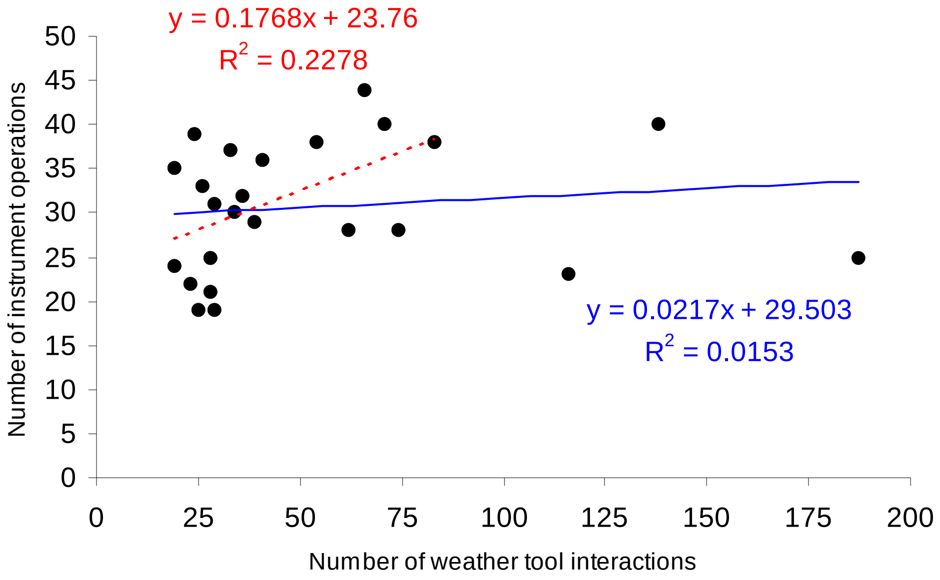
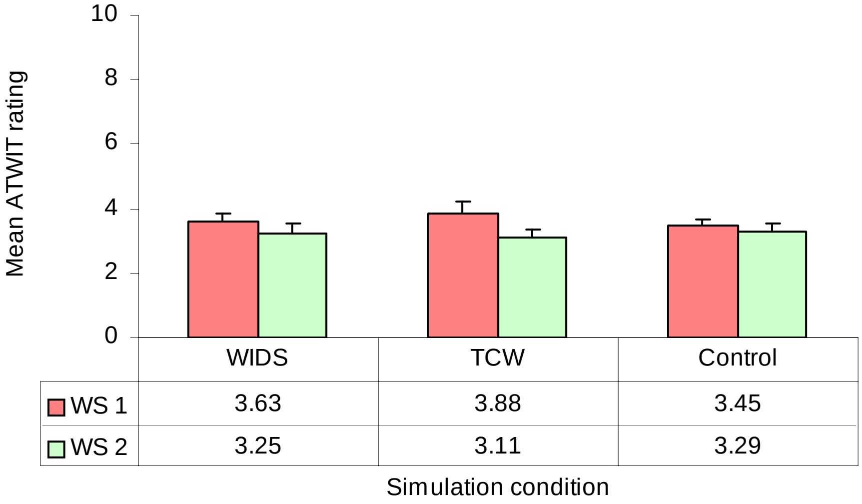


Figure 29. Correlation between the number of weather tool interactions and the number of instrument operations.

6.16 Workload Measures

Our hypothesis that weather tools should reduce controllers' subjective workload (λ_p = .5[WIDS] + .5[TCW] – 1[Control]) was not confirmed by the ATWIT and TLX data. Workload ratings were uniformly low and there were no significant differences in mean ATWIT (see Figure 30) and TLX (see Figure 31) ratings between weather tool conditions (WIDS and TCW) and the Control condition for WS 1 or WS 2.

However, to interpret the subjective ratings in Figure 30 accurately, we must also consider the number of aircraft handled by controllers during these three conditions. During the Control condition, controllers handled on average 4-6% fewer aircraft as compared to the WIDS and TCW conditions. Therefore, controllers were in fact able to ‘regulate’ their workload during Control conditions by accepting fewer arrivals. In the WIDS and TCW conditions, controllers handled more aircraft without a corresponding increase in workload ratings because they could use advanced weather information.



	WIDS	TCW	Control
🟥 WS 1	3.63	3.88	3.45
🟩 WS 2	3.25	3.11	3.29

Figure 30. Mean ATWIT ratings by weather scenario and simulation condition. The rating scale anchors are 1 = *low workload* and 10 = *high workload*. The error bars are *SE*.

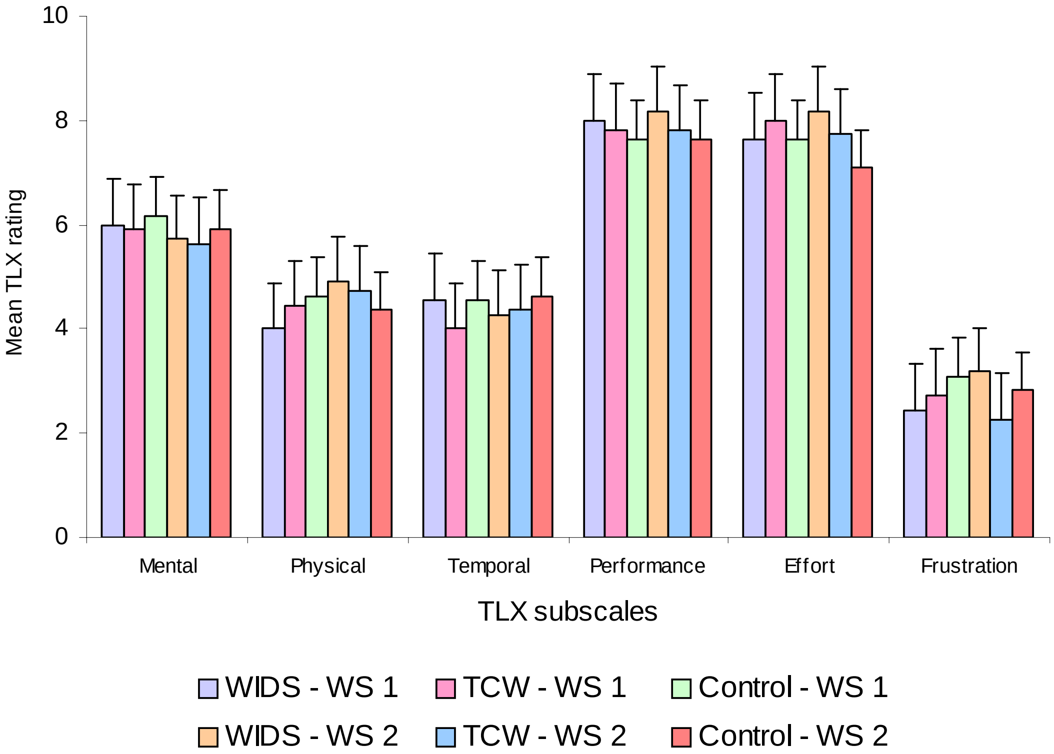


Figure 31. Mean TLX ratings by weather scenario and simulation condition. The rating scale anchors are 1 = *extremely low* and 10 = *extremely high*. The error bars are *SE*.

Our hypothesis was confirmed by results from controller ratings on post-scenario questions. Figure 32 shows mean controller ratings for workload reductions for WIDS, TCW, and Control conditions during WS 1 and WS 2. There was a significant one-tailed contrast for WS 1 $t(10) = 2.19$, $p = .0.27$, ($L = 2.05$, 95% *CI* [.35 to 3.74], $SD = 3.10$, $r_{\text{contrast}} = .57$) and for WS 2 $t(10) = 3.28$, $p = .004$, ($L = 2.73$, 95% *CI* [1.22 to 4.24], $SD = 2.76$, $r_{\text{contrast}} = .72$), indicating that weather tool interaction during WIDS and TCW conditions reduced controllers' perception of *overall* workload more compared to the Control condition.

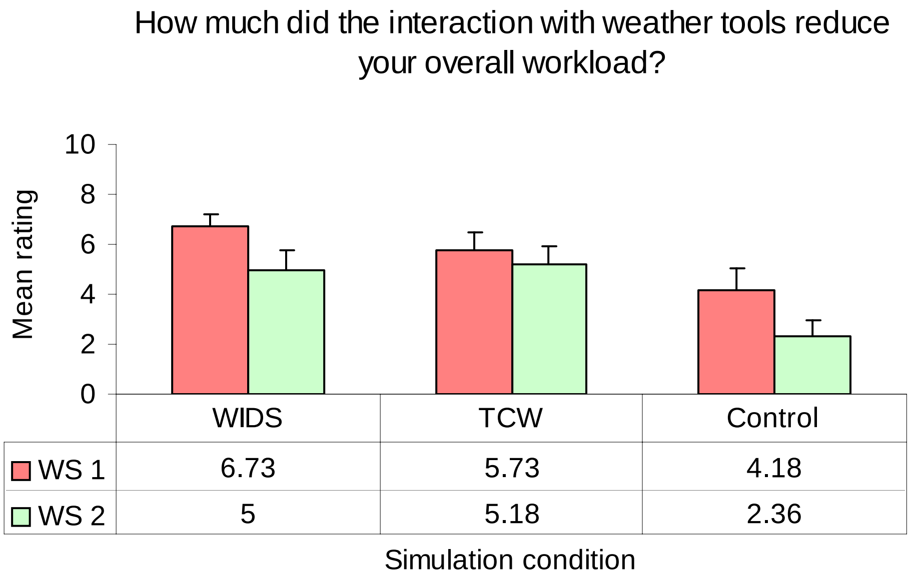


Figure 32. Mean ratings of overall workload reductions due to weather tools interactions. The rating scale anchors are 1 = *none at all* and 10 = *a great deal*. The error bars are *SE*.

6.17 SME Over-The-Shoulder Performance Ratings

For the SME over-the-shoulder performance ratings, we used a standard form developed for instructor certified air traffic control specialist for evaluations of controller performance in simulation environments (see Willems et al., 1999; Appendix D). The SME over-the-shoulder performance ratings were in the high range on the 8-point scales. However, ratings were very similar across simulation conditions. There was a significant one-tailed contrast $t(10) = 1.85$, $p = .047$ ($L = .41$, 95% CI [.01 to .81], $SD = .74$, $r_{\text{contrast}} = .50$) for the ratings of detecting pilot deviations from control instructions during WS 1, indicating that controllers performed better during WIDS ($M = 6.36$, $SE = .31$) and TCW ($M = 6.45$, $SE = .31$) conditions compared to the Control ($M = 6.0$, $SE = .33$) condition. There was also a significant one-tailed contrasts for the ratings of preplanning control actions $t(10) = 3.26$, $p = .004$ ($L = .77$, 95% CI [.34 to 1.17], $SD = .79$, $r_{\text{contrast}} = .72$) during WS 1, with higher ratings for the WIDS ($M = 6.36$, $SE = .53$) and TCW ($M = 6.82$, $SE = .26$) conditions compared to the Control ($M = 5.82$, $SE = .46$) condition. Finally, there was a significant one-tailed contrast for the ratings of overall prioritizing $t(10) = 2.89$, $p = .008$ ($L = .46$, 95% CI [.17 to .74], $SD = .52$, $r_{\text{contrast}} = .67$) during WS 1, indicating that controllers performed better overall prioritizing during WIDS ($M = 6.27$, $SE = .36$) and TCW ($M = 6.45$, $SE = .25$) conditions compared to the Control ($M = 5.91$, $SE = .32$) condition.

Exploratory analyses between tool conditions (1[WIDS] – 1[TCW]) revealed a significant difference in SME ratings for WS 1 where providing additional ATC information was rated as higher during TCW ($M = 6.64$, $SE = .15$) conditions compared to WIDS ($M = 6.09$, $SE = .34$) conditions $t(10) = -2.63$, $p = .025$ ($L = -.55$, 95% CI [-1.01 to -.08], $SD = .69$, $r_{\text{contrast}} = .64$). For WS 2, we found significantly higher ratings for TCW conditions compared to WIDS conditions for the following performance ratings (the means, *SE,* and contrast results are shown in Table 7):

1. Maintaining separation and resolving potential conflicts.
2. Maintaining awareness of aircraft positions.
3. Ensuring positive control.
4. Correcting own errors in a timely manner.
5. Overall attention and situation awareness.
6. Providing coordination.
7. Providing overall control information.

Table 7. Mean Ratings and Analysis Results for Seven SME Performance Ratings.

Rating	**WIDS** ***M(SE)***	**TCW** ***M(SE)***	***t*(10)**	***p***	***L***	**95% *CI***	***SD***	r_{contrast}
1	5.82 (.44)	6.27 (.30)	-2.89	.016	-.91	-1.61, -.21	1.04	.67
2	6.0 (.43)	6.45 (.34)	-2.67	.024	-.73	-1.33, -.12	.90	.65
3	5.73 (.49)	6.45 (.34)	-2.67	.024	-.73	-1.33, -.12	.90	.65
4	6.09 (.41)	6.64 (.31)	-3.46	.006	-.55	-.90, -.19	.52	.74
5	5.91 (.37)	6.36 (.31)	-2.89	.016	-.45	-.81, -.10	.52	.67
6	6.09 (.49)	6.64 (.45)	-3.46	.006	-.55	-.90, -.19	.52	.74
7	6.0 (.44)	6.36 (.30)	-2.39	.038	-.36	-.70, -.03	.50	.60

In summary, SME over-the-shoulder performance ratings were mostly similar across simulation conditions. Our analysis only revealed significantly higher ratings for controller performance in tool conditions (WIDS and TCW) compared to the Control condition for detecting pilot deviations from control instructions, preplanning control actions, and overall prioritizing during WS 1. We found no significant differences in SME ratings for controller performance between weather tool conditions and the Control condition in WS 2. Using exploratory analyses, we found small but significant differences in SME ratings of controller performance between the TCW and the WIDS conditions. For eight performance ratings, SME ratings were higher for controllers during the TCW condition compared to the WIDS condition. Potentially, these higher performance ratings could reflect an increased efficiency for TCW conditions where traffic data and weather data are spatially integrated.

7. Discussion

To our knowledge, the present study is the first, high fidelity, human-in-the-loop simulation ever conducted with advanced weather tools at the controller workstation. While previous research has explored various topics related to ATC weather information display, no previous study has systematically investigated advanced weather tools and their impact on *tactical* operations in the TRACON domain (Ahlstrom & Della Rocco, 2003).

From a tactical operations perspective, we found an impact of weather tools on controller efficiency, with increases in sector throughput (i.e., completed flights) of 6% to 10%. This corresponds to a significant increase in efficiency, and although these are simulation results, there are reasons to believe that many terminal sectors affected by substantial thunderstorm seasons could see a similar increase in efficiency (Krozel, Capozzi, Andre, & Smith, 2003). By providing enhanced weather information at the workstation, we enhance controllers’ ability to detect approaching weather, monitor its movement, and understand its effect on future operations. This should increase controllers' efficiency for timing of arrivals, for vectoring and adjustment of flow and sequencing, and for runway selection. In addition to increased sector throughput, our results also point to potential benefits for pilots when controllers have access to enhanced weather information. During the simulation, controllers issued weather sequences as they became available, reported storm intensity and movements, delivered reports about changing conditions, and explained reasons for approach changes to pilots when they were necessary. In short, pilots should also benefit from the increase in controller WSA.

Although the use of weather tools positively impacted controller efficiency and WSA, we failed to find significant effects of weather information on many other simulation outcomes. First, there were no significant effects from weather tools during WS 1 besides the subjective perception by controllers that weather tools reduce workload. This implies that our weather tools were not effective under all types of adverse weather conditions. If a storm moves slowly and contains a lot of cell 'pop-up' and cell growth, as was the case in WS 1, there is little that controllers can do and weather information has no effect. Of course, in this case the weather tools will still contribute to an increased controller WSA, but without any possibility to translate this increased WSA into more efficient control operations, the net effect will be zero.

Second, we failed to find any evidence of significant effects from weather tools in both WS 1 and WS 2 for simulation outcomes like controllers' use of control commands (i.e., altitude, speed), holds, distance flown per aircraft, and the number of controller-pilot communications. For some of these outcomes, we had no a priori hypothesis about the magnitude or direction of effects. The immediate availability of advanced weather information at the controller workstation could have potentially affected these outcomes in either way. For example, it was just as feasible that communications could have increased or decreased as a function of increased controller WSA. Similarly, the use of control commands could have also potentially increased or decreased as a function of increased WSA. However, the results from the present study suggest that weather information has no direct effect on these outcomes. But the fact that we failed to find evidence of significant effects in the present simulation does not mean that there are no effects on these outcomes. Simulations with different sector characteristics, arrival flows, runway configurations, and traffic patterns, could potentially lead to effects that we failed to find in the present study.

After analyzing the weather tool usage by controllers, we found that the Precipitation Forecast and the Weather Loop were used more frequently than the Storm Motion tool. All three tools provide information about the direction of storm cell movements and future storm cell positions. However, because the Storm Motion tool is static, it requires users to perform some mental integration to infer *situational dynamics* (i.e., by integrating motion vectors, wind speed, and extrapolated positions). In contrast, the Precipitation Forecast and the Weather Loop tools are dynamic predictions of storm movements. Dynamic predictions of storm cell movements can potentially reveal future affordances and airspace constraints in a more direct way, thereby providing controllers with goal-relevant information. In this simulation, when faced with the choice of using static or dynamic weather information, controllers chose the latter.

In the current simulation, we found little controller interaction with the Echo Top and Gust Front tools, and no direct impact from the Wind Shear and Microburst alerts. The location and movements of Gust Fronts and their associated changes in wind speed are important types of information when they occur near runways. Similarly, Wind Shear and Microburst information are especially important when these phenomena impact the runway or final approach course.

Our pre-recorded ITWS data contained Gust Front information and Wind Shear and Microburst alerts in the scenarios. However, in the weather scenarios used for the present study, this information was always superimposed on weather Levels 4-6 where no aircraft were allowed to penetrate. In fact, controllers were explicitly instructed to keep aircraft away from these areas. It is possible that because controllers focused on severe weather avoidance, there was little direct tactical use for Echo Top and Gust Front information. Similarly, the Wind Shear and Microburst alerts also occurred in association with Level 4-6 areas, potentially limiting the use of this information since controllers avoided these areas altogether. However, we should not use this lack of use to infer that these weather tools would not be useful for field operations. In fact, feedback from controllers indicated that if Wind Shear and Microburst information were available in the field, controllers could transfer it to pilots who should benefit from receiving this information early on during arrivals.

Although some forms of weather information provide more benefits for tactical operations than others, *we want to emphasize that any timely and accurate advanced weather information not currently at the workstation could benefit controller WSA*. Ideally, weather information should be graphical, not text-based. If we look at the current way controllers receive weather updates from METARs, AIRMETs, and SIGMETs, we can get insight into the limitations of human cognition when processing text-based weather information. When controllers receive this information, usually on printed paper strips, they broadcast it to aircraft within their sector. From a pilot perspective, these broadcasts provide important weather information useful for route planning (Spirkovska & Lodha, 2002). From a controller perspective, it is less clear whether this information improves controller WSA or aids controllers in understanding effects on future ATC operations. In fact, we found that presenting controllers with text-based or verbal weather information during Control conditions limited controllers' ability to perform instrument operations (i.e., number of completed flights). Comments from controllers during debriefings indicated that they found it difficult to translate text-based and verbal information into mental representations of hazardous weather areas and to foresee future effects of weather on sector traffic. Controllers explicitly stated that getting METARs, SIGMETs, and even PIREPs, did not provide them with a good mental picture of projected weather within the sector. Providing weather information in graphical form at the workstation (WIDS or TCW) made this task much easier because graphical information affords the user direct information 'pick-up'. With this information, controllers can act on information directly without constructing a mental image that might require even further mental elaboration.

Although we found that providing weather information on both the WIDS and TCW was beneficial to controllers, we did see differences in the simulation data that could have been due to presentation mode idiosyncrasies. For example, both presentation modes differed in respect to the spatial and temporal presentation of traffic and weather data, and in the potential for creating display clutter. During WIDS conditions, we found that controllers performed significantly more heading commands compared to TCW conditions. This was possibly due to the spatial separation of weather and traffic data that would have led to a larger number of corrective heading commands by controllers during WIDS operations. Another issue related to the spatial separation of data is the amount of 'heads-up' time for controller using the WIDS display. Potentially, controllers could have spent a large amount of time looking up at the WIDS, time that could have been spent focusing on the traffic data. However, this did not seem to be the case during our simulation. There was, however, a tendency for controllers to display advanced weather products for longer durations during WIDS conditions compared to TCW conditions.

This interaction pattern was likely the result of increased display clutter for superimposed traffic and weather data on the TCW. Despite these idiosyncratic effects, it seems like controllers can safely and effectively use both presentation modes for tactical operations. Based on subjective reports from controllers, we found no clear preference for either presentation mode. Weather presentation on WIDS and TCW were clearly preferred over receiving information from a supervisor. Controllers who reported preferring WIDS stated that they liked WIDS because weather information was instantly available but did not interfere with the traffic display. Those controllers who preferred receiving weather information on the TCW felt that on the TCW, there was less work involved in correlating weather information with current aircraft positions, and that there was no need to divert attention away from the traffic when viewing weather information.

The degree of usability of advanced weather tools is highly contingent upon interaction modes and display characteristics. In the current simulation, we used toolbar activation where controllers activated weather tools using a designated set of toolbar buttons. While this interaction mode is functional for infrequent tool interactions, it is unsuitable for tools that are activated frequently by the user. Feedback from controllers during the simulation supports this conclusion. Controllers reported that certain toolbar buttons, especially the Weather Loop and Precipitation Forecast buttons, would have worked better as separate ‘toggle switches’ to allow for easier switching between tools. Controllers also reported that toolbar interaction diverted attention away from the traffic, which was especially distracting during frequent tool usage. Based on these results, we recommend the use of an auxiliary keypad for weather tool interaction, similar to the interactive keypad found at Display System Replacement (DSR) workstations for adjusting vector lines. By implementing this type of interaction, controllers could easily manipulate weather tools without diverting attention from traffic on the situation display.

Finally, we did not investigate optimal color palettes for the display of traffic information and weather objects in the current study. The sole purpose of the present study was to investigate the operational benefits and human factors issues associated with providing advanced weather information to controllers. Throughout the study, we used a STARS simulator and prototypes of weather tools developed based on previous research (Ahlstrom et al., 2004). Our basic color palette was similar to the current STARS implementation with six levels of precipitation, with additional colors for the presentation of advanced weather information (Figure 8b). As a result, our displays were multicolored and deviated somewhat from current guidelines of color usage on ATC displays (Ahlstrom & Longo, 2003). To optimize display legibility, controllers manipulated salience by adjusting the luminance contrast of display objects. For simulation purposes, the interface was operational and adequate for an assessment of the use of advanced weather information. To implement similar weather tools for current TRACON displays with color capabilities, however, would require a more thorough approach using predefined color palettes especially designed for layered data and a large number of display objects. While color-coding has potential benefits for ATC displays, it presents several human factors challenges. Legibility, salience manipulation (clutter avoidance), and color recognition are the main usability issues at stake. As more interface symbols are color coded, the possible combinations of foreground and background colors rapidly increase. Aircraft symbols and alphanumeric data move and must be legible on all backgrounds (precipitation levels and advanced weather information) across the display area. With an increasing number of symbol/background color combinations, users risk producing suboptimal usability. Interface designers can avoid such detrimental avenues by using proposed color palettes for layered data with large numbers of display objects (Reynolds, 1994; Van Laar, 2001). The goal is to achieve good margins of legibility and color identification for all symbols and color combinations, and to prevent display clutter from posing usability and possibly even safety risks.

8. Recommendations

Based on simulation results, we make the following recommendations for weather tool developments for TRACON controllers.

There are currently no dynamic storm forecast tools developed for terminal controllers. Therefore, weather research needs to develop (1) a dynamic two-frame storm motion tool that first shows the current storm cell positions, and then immediately shows the predicted positions ten minutes into the future. The displayed combination of storm precipitation levels in this two-frame display should be user-adjustable (e.g., Levels 2, 3, 4, 5, and 6, or Levels 2, 4, and 6). The display duration for the predicted positions should also be user-adjustable, and include a range of selectable values around 2 seconds. Upon activation by the user, the tool should continuously display the two-frame sequence until de-activated.

Furthermore, weather research needs to develop (2) a dynamic multi-frame loop of predicted storm cell positions that starts from the current positions and incrementally moves to the predicted positions 20 minutes into the future. There should be no animation of storm history positions (i.e., storm cell positions prior to the current storm cell positions). The displayed combination of storm precipitation levels in the multi-frame loop should be user-adjustable (e.g., Levels 2, 3, 4, 5, and 6, or Levels 2, 4, and 6). For each incremental movement of the storm positions, there should be a corresponding numeric display of the forecast time (i.e., minutes into the future). Upon activation by the user, the tool should continuously display the multi-frame sequence until de-activated.

Finally, during the current simulation, weather cell penetrations (Levels 4-6) did occur during weather tool conditions, despite the controller’s responsibility to keep aircraft away from these levels. Most penetrations were caused by weather cell ‘pop-ups’ that controllers were unable to foresee. In order for storm forecast tools to be as effective as possible, weather research needs to develop (3) dynamic storm tools that predicts the ‘growth’ and ‘decay’ of storm cells during the predictive part of the dynamic storm movements.

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Acronymns

AIRMET	Airman's Meteorological Information
AOJ	Area of Jurisdiction
APA	American Psychological Association
ARTS	Automated Radar Terminal Systems
ASOS	Automated Surface Observing System
ATWIT	Air Traffic Workload Input Technique
CARTS	Color ARTS Display
CHI	Computer Human Interface
CWA	Cognitive Work Analysis
DASI	Digital Altimeter Setting Indicator
DESIRE	Distributed Environment for Simulation, Rapid Engineering, and Experimentation
DFW	Dallas Fort Worth
DSR	Display System Replacement
FAA	Federal Aviation Administration
GA	General Aviation
GENERA	Generic TRACON Airspace
IDS4	Information Display System 4
ITWS	Integrated Terminal Weather System
MANOVA	Multivariate Analysis of Variance
METAR	Aviation Routine Weather Report
NAS	National Airspace System
NHST	Null Hypothesis Significance Tests
NTSB	National Transportation Safety Board
NWS	National Weather Service
PIREP	Pilot Reports
POG	Point of Gaze
RDHFL	Research Development and Human Factors Laboratory
RVR	Runway Visual Range
SAWS	Stand Alone Weather Sensors
SE	Standard Errors
SIGMET	Significant Meteorological Advisory

SME	Subject Matter Expert
SOP	Standard Operating Procedures
SPECI	Special Weather Report
STARS	Standard Terminal Automation Replacement System
TCW	Terminal Controller Workstation
TDWR	Terminal Doppler Weather Radar
TFSI	Task Force on Statistical Inference
TGF	Target Generator Facility
TLX	Task Load Index
TRACON	Terminal Radar Approach Control
WARP	Weather and Radar Processor
WIDS	Weather Display System
WPI	Weather Proximity Index
WS	Weather Scenario
WSA	Weather Situation Awareness
WSP	Weather System Processor

Appendix A

Post-Scenario Questionnaire

Post-Scenario Questionnaire

Question	**Scenario**	**Sector**	**WIDS**		**TCW**		**CONTROL**	
			M	*SD*	***M***	***SD***	***M***	***SD***
Rate your overall level of ATC performance during this scenario.	1	East	7.4	.6	7.2	1.8	8.4	1.1
		West	8.0	1.1	7.8	1.7	7.5	1.9
	2	East	8.2	1.5	7.8	1.3	7.8	0.5
		West	8.5	1.5	8.2	1.6	8.2	1.6
Rate your level of situational awareness during this scenario.	1	East	7.6	0.9	7.4	1.1	7.8	1.3
		West	8.8	0.8	8.7	0.8	8.5	1.1
	2	East	8.0	1.2	7.2	0.8	7.0	1.7
		West	8.3	1.4	8.0	1.1	7.3	1.8
Rate the performance of the simulation pilots in terms of their responding to control instructions and providing read backs.	1	East	9.4	.6	8.4	1.1	9.0	1.0
		West	9.17	0.75	9.17	0.75	9.3	1.2
	2	East	9.0	0.7	8.4	1.1	9.2	1.3
		West	9.17	0.75	8.8	0.75	9.17	0.75

Extremely Poor ②③④⑤⑥⑦⑧⑨⑩ Extremely Good

Question	**Scenario**	**Sector**	**WIDS**		**TCW**		**CONTROL**	
			M	***SD***	***M***	***SD***	***M***	***SD***
How much interaction with weather tools occurred during this scenario?	1	East	6.4	1.5	7.0	0	4.2	1.6
		West	7.8	1.7	7.7	2.0	2.7	1.9
	2	East	6.6	1.1	6.0	1.9	3.6	2.0
		West	7.2	1.8	7.2	2.3	3.7	3.1
How much did the interaction with weather tools reduce your overall workload during this scenario?	1	East	6.4	1.3	4.6	2.9	4.8	3.6
		West	7.0	1.7	6.7	1.8	3.7	2.4
	2	East	5.4	2.7	3.2	1.6	2.6	1.8
		West	4.7	2.6	6.8	1.6	2.2	2.4
How much coordination with your supervisor and TMU occurred during this scenario?	1	East	5.0	1.6	4.6	0.9	5.2	0.5
		West	3.3	1.2	3.5	1.4	3.3	1.5
	2	East	3.0	1.7	2.8	1.5	4.2	1.3
		West	3.0	1.8	2.8	1.5	2.7	0.5
How much weather coordination with your supervisor/TMU occurred?	1	East	[redacted]	[redacted]	[redacted]	[redacted]	4.4	1.8
		West	[redacted]	[redacted]	[redacted]	[redacted]	3.0	2.0
	2	East	[redacted]	[redacted]	[redacted]	[redacted]	4.0	1.7
		West	[redacted]	[redacted]	[redacted]	[redacted]	2.67	1.75

None At All ①②③④⑤⑥⑦⑧⑨⑩ A Great Deal

Question	**Scenario**	**Sector**	**WIDS**		**TCW**		**CONTROL**	
			M	*SD*	*M*	*SD*	*M*	*SD*
Rate the difficulty of this scenario.	1	East	6.4	0.55	5.60	1.1	5.6	1.5
		West	4.8	1.47	5.5	1.5	6.8	1.9
	2	East	6.2	1.6	4.6	1.5	5.2	1.48
		West	5.8	1.9	5.8	1.9	5.8	2.3
Overall, how easy was it to use (WIDS/the weather information on the TCW/ the weather information from your supervisor/TMU) during this scenario?	1	East	6.2	1.6	6.2	2.39	7.6	1.8
		West	7.67	1.5	7.8	1.9	7.8	2.79
	2	East	6.6	2.19	6.4	2.4	5.8	1.79
		West	7.17	2.2	6.8	2.86	8.5	1.5
How easy was it to access (weather information from the WIDS/ weather information from the TCW/ this weather information) when needed?	1	East	6.4	1.95	6.4	2.3	6.6	2.4
		West	8.17	1.7	7.67	2.07	6.0	2.8
	2	East	6.4	2.19	6.8	2.28	5.6	1.8
		West	7.3	2.5	6.67	2.4	6.8	3.5

Extremely Difficult ①②③④⑤⑥⑦⑧⑨⑩ Extremely Easy

Question	**Scenario**	Sector	**WIDS**		**TCW**		**CONTROL**	
			M	*SD*	*M*	*SD*	*M*	*SD*
Rate your workload due to communications with pilots during this scenario.	1	East	4.8	2.4	5.6	2.1	5.6	0.9
		West	5.7	2.9	5.0	1.3	5.0	2.8
	2	East	5.2	2.8	5.0	1.6	6.6	1.5
		West	4.5	3.1	5.3	3.4	4.8	2.9
Rate your workload due to weather during this scenario.	1	East	6.8	0.8	7.4	0.9	6.2	2.2
		West	6.5	0.8	6.3	1.8	7.0	1.4
	2	East	4.8	2.4	4.8	3.0	5.0	1.6
		West	5.7	1.8	5.5	1.6	6.2	2.5
Rate your workload due to coordination with your supervisor and TMU during this scenario.	1	East	3.4	1.1	3.4	1.3	3.8	1.6
		West	2.5	1.8	2.8	1.8	2.5	1.8
	2	East	2.0	0.7	2.4	1.7	3.2	1.5
		West	2.2	1.2	2.2	0.8	2.3	1.2
Rate your workload due to interactions with the weather tools during this scenario.	1	East	4.8	0.8	5.6	2.2	3.0	2.1
		West	5.0	2.6	5.7	1.8	2.5	2.0
	2	East	4.8	1.1	5.2	2.6	2.6	1.8
		West	5.7	2.3	4.3	1.5	2.8	2.2
Rate the difficulty of accessing different (information pages on the WIDS/ weather information on the TCW).	1	East	3.8	2.17	4.0	2.55		
		West	3.0	1.55	4.67	2.66		
	2	East	2.6	1.3	4.2	2.77		
		West	4.3	2.25	5.5	1.87		
Rate the difficulty in correlating weather information on the WIDS with the traffic and sector map on the TCW	1	East	2.4	2.07				
		West	2.67	1.37				
	2	East	2.6	1.95				
		West	2.8	1.3				
Extremely Low ①②③④⑤⑥⑦⑧⑨⑩ Extremely High								

Question	**Scenario**	**Sector**	**WIDS**		**TCW**		**CONTROL**	
			M	***SD***	***M***	***SD***	***M***	***SD***
How often did you feel that the weather information caused clutter on (the WIDS Display/the TCW)?	1	East	2.6	2.07	3.2	2.59		
		West	2.67	2.4	4.5	3.0		
	2	East	1.6	0.89	3.2	2.59		
		West	2.3	1.37	4.5	2.07		
Never ①②③④⑤⑥⑦⑧⑨⑩ Always								

Question	**Scenario**	**Sector**	**WIDS**		**TCW**		**CONTROL**	
			M	***SD***	***M***	***SD***	***M***	***SD***
What impact did (WIDS/ the weather information/ the weather information from your supervisor/TMU) have on your workload?	1	East	6.6	3.2	5.8	1.79	5.2	0.45
		West	6.5	2.5	5.8	2.1	5.5	1.6
	2	East	7.4	0.89	6.4	1.5	6.8	1.3
		West	5.3	1.86	6.5	2.7	6.17	1.9
What impact did (WIDS/ the weather information/ the supervisor/TMU coordination) have on your workload?	1	East	6.6	3.2	5.8	1.79	4.5	2.89
		West	6.5	2.5	5.8	2.1	5.5	1.38
	2	East	7.4	0.89	6.4	1.5	6.0	3.08
		West	5.3	1.86	6.5	2.7	5.0	1.4
Negative (increased) ①②③④⑤⑥⑦⑧⑨⑩ Positive (decreased)								

Question	**Scenario**	**Sector**	**WIDS**		**TCW**		**CONTROL**	
			M	*SD*	*M*	*SD*	*M*	*SD*
What impact did (WIDS/ the weather information/ the weather information from your supervisor/TMU) have on your situational awareness?	1	East	7.4	0.55	6.4	1.3	4.6	1.8
		West	7.3	1.75	7.67	1.5	5.8	1.47
	2	East	7.2	0.8	6.75	0.5	4.6	2.07
		West	7.17	1.3	7.8	1.3	6.0	1.55
What impact did (WIDS/ the weather information) have on your ability to give advisories pilots?	1	East	7.6	0.55	7.8	1.1		
		West	7.8	1.17	8.3	1.5		
	2	East	7.2	0.8	7.0	0.8		
		West	7.0	2.76	8.3	1.37		
Negative (decreased) ①②③④⑤⑥⑦⑧⑨⑩ Positive (increased)								

NASA-TLX

Question	**Scenario**	**Sector**	**WIDS**		**TCW**		**CONTROL**	
			M	*SD*	*M*	*SD*	*M*	*SD*
Rate your mental demand during this scenario.	1	East	5.4	0.89	5.8	1.3	5.4	1.3
		West	6.5	2.26	6.0	2.1	6.8	2.6
	2	East	6.4	1.1	5.0	1.4	5.4	1.5
		West	5.17	2.48	6.17	2.99	6.3	1.86
Rate your physical demand during this scenario.	1	East	4.0	1.7	4.6	2.19	4.4	1.5
		West	4.0	1.79	4.3	2.66	4.8	2.79
	2	East	4.6	2.3	4.4	1.8	4.8	1.3
		West	5.17	3.25	5.0	3.1	4.0	2.5
Rate your temporal demand during this scenario.	1	East	3.8	1.6	4.2	1.6	3.6	1.8
		West	5.17	2.1	3.8	1.17	5.3	2.5
	2	East	4.0	2.2	3.4	2.07	4.8	2.28
		West	4.5	2.07	5.17	2.4	4.5	1.97
Rate your performance during this scenario.	1	East	7.6	0.55	7.4	1.5	8.0	1.0
		West	8.3	0.8	8.17	1.3	7.3	1.75
	2	East	7.6	1.1	7.4	1.1	7.6	1.1
		West	8.67	1.2	8.17	1.6	7.67	1.5
Rate your effort during this scenario.	1	East	7.0	1.2	7.0	1.58	6.6	2.4
		West	8.17	2.3	8.8	1.17	8.5	1.38
	2	East	7.8	0.84	7.0	1.87	6.4	1.8
		West	8.5	1.5	8.3	2.25	7.67	2.66
Rate your frustration during this scenario.	1	East	2.6	1.5	3.2	1.79	2.8	2.49
		West	2.3	1.5	2.3	1.2	3.3	2.4
	2	East	4.2	3.27	2.8	2.17	3.8	2.77
		West	2.3	2.3	1.8	0.98	2.0	1.26
Extremely Low ①②③④⑤⑥⑦⑧⑨⑩ Extremely High								

Additional comments regarding WIDS:

- When you use the weather loop, I would prefer the loop only show the wx levels I have selected on the 6 level precip to watch.
- I like the forecast feature. It helps me to get an idea about when to tell ctr to hold.
- WIDS is a good tool if it is the only option. However, integrating the information into the TCW would be more useful and greatly reduce time spent with eyes off traffic.
- As stated before, need more control to turn off the levels when the wx loop is moving!
- Need to incorporate more toggle switches (on-off) to change from sigmets back to what you were previously displaying.
- For preplanning, I found the display very helpful.
- The sigmet button needs to toggle off by clicking it again instead of having to scroll up to weather to turn it off. The same thing with the wx loop button. Also, wx loop too long would be better to have 5 min before to 15 min projected. Also would be great if there was a clock associated with weather loop so you could see the time associated with the movement. The wx loop moves quickly which is nice to get a quick outlook, but if there were a clock counting up the minutes, it would help a lot.
- Precipitation forecast- (to quick to tell). Also, it should only display level 4, 5, 6.

Additional comments regarding weather components on the STARS TCW:

- This was the first scenario without the WIDS and I prefer to look at the weather display on WIDS over directly on my scope. However, with more familiarity, that might change.
- As I became more familiar with them, the more I use them.
- Having to click on the ITWS button before selecting a weather information item and then click done to go back to slewing on the scope takes attention away from traffic for too long. It would be better to have these items on the main menu bar of the TCW. Also, having to click on wx loop again to turn it off is a hassle. It would be better if it just shut off when you click done or better yet, if it went through one cycle then went off like to precip forecast does.
- I don't like how the mouse pointer gets stuck up in the tool bar. There should be just another small tool bar. And, the precip. forecaster should be in 10 min increments, not 15! It should match with the other 10 min increment functions.
- Would have been nice to see a time stamp on forecast precip to relay to pilots. (Not available on scope).
- I know that it will be different in the field, but I needed to change the intensity of the precip.
- Need-minute-increments for the wx loop!
- Wx loop not being time caused problems.
- Previous location of the wx loop on TCW increases workload.
- The wx precipitation forecast did not work as well.

Additional comments regarding the weather information you received from the supervisor/TMU:

- It is definitely more distracting reading the weather and sigmets from paper copies then having them on the WIDS or STARS scope.
- Some sort of projection of where cells were moving would have been helpful.
- It was too difficult to stop watching the scope in order to read a newly handed piece of paper. If the info was on the scope it would have been easier.

Do you have any comments or clarifications about these NASA-TLX questions?

- Some of these are hard to complete because the demands for interest changed. At some times they were harder than others.
- Still hard because of the variations in traffic intensity and workload. When you are busy obviously the demands are higher as are the effort and frustration levels. Similarly, when they are lower (demands), the effort and frustration drop as well.
- Are these really CAMI questions?
- Wx loop time preview area should be moved to different location.

	Of all the WIDS/TCW information components, which ones did you actually use during this scenario? (Check all that apply!) or What weather information did you coordinate with your supervisor/TMU? (Check all that apply!)			What WIDS/TCW information did you use most frequently during this scenario? (Check one!)		What WIDS/TCW information do you think was NOT useful at all during this scenario? (Check all that apply.)		What WIDS/TCW information do you think is essential for safe and efficient control of traffic during this scenario? (Check all that apply.)		What weather information do you think was missing during this scenario?
	WIDS	**TCW**	**Control**	**WIDS**	**TCW**	**WIDS**	**TCW**	**WIDS**	**TCW**	**Control**
Gust front line	15	15	0	3	3	2	0	12	14	10
Gust front predictions	0	2	0	0	0	19	20	2	1	2
Echo tops	1	0	2	0	0	11	12	4	2	5
Lightning	18	17	3	9	5	2	2	17	14	14
Storm motion	17	16	1	8	3	5	4	11	11	15
Cell movements	16	16	0	6	11	2	0	14	12	13
Storm growth and decay	1	6	0	0	0	11	2	5	9	1
Predictive and historical loops	1	16	0	0	10	4	0	4	19	5
Icing	14	10	5	9	0	0	1	16	11	1
Microburst	9	5	10	3	0	1	1	9	9	1
6-Level precipitation	7	0	7	1	0	3	0	8	0	4
METARS	1	0	1	0	0	6	0	3	0	1
SPECI	12	0	6	1	0	4	0	6	0	3
RVR	4	0	2	1	0	5	0	2	0	2
ILS monitor information	1	0	1	0	0	1	0	1	0	0
TAF	0	0	0	0	0	0	0	0	0	0
AIRMET	0	0	0	0	0	0	0	0	0	0
SIGMET	0	0	0	0	0	0	0	0	0	0
Convective SIGMET	0	0	0	0	0	0	0	0	0	0
CWA	0	0	0	0	0	0	0	0	0	0
Other, specify:	Pireps-if they could be incorporated into the WID after being disseminated (similar to the IDS-4/ACE-IDS)		Pireps Turbulence (chop) Precipitation levels			I feel that most of this info is useful, I just did not use it.		Pireps		

Appendix B

Exit Questionnaire

Exit Questionnaire

Question	***M***	***SD***
Rate the realism of the overall simulation experience compared to actual ATC operations.	7.64	1.43
Rate the realism of the simulated weather scenarios compared to actual field operations during adverse weather.	8.50	.85
Rate the realism of the simulation STARS hardware compared to actual STARS equipment.	8.75	1.26
Rate the realism of the simulation STARS software compared to actual STARS functionality.	8.75	1.26
Rate the realism of the simulation generic airspace compared to actual NAS airspace.	7.64	1.86
Rate the realism of the simulation traffic scenarios compared to actual NAS traffic.	7.82	1.40
Rate the realism of the simulated control room environment compared to actual field operations.	7.55	1.63
Extremely Unrealistic ①②③④⑤⑥⑦⑧⑨⑩ Extremely Realistic		

Question	***M***	***SD***
To what extent did the oculometer interfere with your ATC performance?	1.86	1.21
To what extent did the ATWIT online workload rating technique interfere with your ATC performance?	2.38	1.41
How well did the WIDS enable you to provide useful advisories to pilots?	7.18	2.14
How well did the weather information on TCW enable you to provide useful advisories to pilots?	7.55	1.97
None/Not At All ①②③④⑤⑥⑦⑧⑨⑩ A Great Deal		

Do you have any comments or suggestions for improvement about our simulation capability?

- Final approach course should be depicted to extend at least 10 mile beyond outer marker.
- Extend the final approach course portrayal out further from the LOM.
- I would add some more noise. Other controllers talking, landlines ringing, shout lines. Pilots requesting more.
- I think it is fine. However, if the prefs. could be adjusted as necessary, it may be helpful.

What WIDS information did you most frequently use in the scenarios? (count)

Wx loop - 9
Gust fronts - 5
Precip forecast - 5
Storm motion - 4
6 level weather – 4

What TCW weather information did you most frequently use in the scenarios? (count)

6-level weather - 5
Precip forecast - 5
Wx loop - 3

Gust fronts - 3
Storm motion - 3
METAR, RVR - 1
ITWS – 1

What weather information provided by your supervisor/TMU did you find most useful?

Metar - 3
SIGMET - 3
Special Wx - 3
Did not receive any/None - 2
CWA - 1
RVR - 1
Other:

- Changes in observations.
- Mostly we provided the data pireps, but they did forward information about holding which allowed you to know the flow would discontinue from that direction until releasing them again.

What WIDS information did you never use in the scenarios? (count)

Echo tops - 9
Lightning - 4
Icing - 3
ILS monitor - 2
Precip forecast - 1
Wx loop - 1
Gust front - 1

What TCW weather information did you never use in the scenarios?

Echo tops - 6
Lightning - 4
Gust fronts - 2
Precip forecast - 2
Wx loop - 1
CWA - 1
Sigmet - 1
Icing – 1

In general, what weather information did you most frequently request from your supervisor/TMU?

None (count - 7)
SPECI and RVR reports.
Center flow.
Mostly asked them to pass information.

Do you think that the WIDS was missing some weather information that would have been useful during the scenarios? If so, please elaborate.

- Winds at different altitudes.
- When you choose Airmet/Sigmet, it would work better as an on-off toggle switch. Same with ILS etc. If on the 6 level, you are only using LVL 4-6, only display level 4-6 in the wx loop motion display. Also, on the wx loop, have it continue displaying loop until it is toggled off rather than forcing you to redeploy the button.
- The available information i.e., wx-loop, precip forecast buttons should be toggle switches to allow easier switching between screens. When wx-loop and precip forecast are used, make the display come up indicating only the levels of weather display on the 6-level weather displayed on screen. If all channels disengaged then have all channels depicted if loop or forecast engaged.

Do you think that the weather information on the TCW was missing some information that would have been useful during the scenarios? If so, please elaborate.

- The available information i.e., wx-loop, precip forecast buttons should be toggle switches to allow easier switching between screens. When wx-loop and precip forecast are used, make the display come up indicating only the levels of weather display on the 6-level weather displayed on screen. If all channels disengaged then have all channels depicted if loop or forecast engaged.
- Would have liked gust fronts, forecast, and storm motion.
- MINUTES for the wx loop.
- Gust front

What useful weather information do you think was missing but could have been provided by the supervisor/TMU?

- None - 10
- Anticipated movement of wx cell windshear - 1

Please explain the difference between how you controlled traffic with and without WIDS.

- Very little difference. (count - 2)
- With the WIDS information, I began planning to hold sooner with the forecasts.
- Without WIDS, I could only react to wx as it happened. With WIDS, I could plan ahead to switch approaches.
- With- seemed to have more confidence in letting aircraft come in. Without- I didn't know whether to let them in or not! (into my airspace).
- Had to get pireps for wx info and relay them. (Sounds unprofessional to say we only see rain and don't know where its activity is unless it's at the airport.
- Without the WIDS, I used less tools on the display. With the WIDS, I used gust fronts, more precip (level 3) etc.
- With WIDS, can get more creative in bringing a/c to the airport (don't have to hold as long).
- It enables the controller to pre-plan (not react)-2

Please explain the difference between how you controlled traffic with and without advanced weather information on the TCW.

- Very little difference.
- Harder to preplan without.

- Without advanced weather, I could not predict where the cells would move so I had to give more extreme vectors at times. With wx loop, I could project the movement of the cell and give an initial vector to avoid it.
- With- seemed to have more confidence in letting aircraft come in. Without- I didn't know whether to let them in or not! (into my airspace).
- I felt I was more helpful and safety conscious since I could make better judgments and offer more info.
- With the ITWS functions on the scope, I feel that it was easier to predict when the wx was going to impact the final approach courses. That in turn made it easier to keep the traffic flowing to the airport.
- With the advanced wx info, I was able to plan my arrival capacity because I knew where the wx would be, within reason, in the short term future.
- With WIDS, can get more creative in bringing aircraft to the airport (don't have to hold as long).
- Had to wait longer to stop arrivals.
- Was able to better inform the pilot and preplan sooner.

How well did the weather information on TCW enable you to provide useful advisories to pilots?

- 6 level is great to give the pilots info. I very seldom used the gust fronts and storm motion and wx loop on the TCW preferring to have the ITWS displayed above rather than having the clutter on the TCW. It was very easy to correlate WIDS data with the TCW data. Also, the TCW using ITWS was very awkward having to hit the done button rather than having those functions as simple toggle switches.
- I'd love to see this on my scope.
- I was able to give the pilots a reasonably accurate EFCT when I held.

Please explain the difference between controlling traffic with weather information provided by the supervisor/TMU, versus controlling traffic with weather information on the WIDS or TCW.

- If the information is available on WIDS or TCW, there is no chance of miscommunication or misunderstanding on the part of the controller.
- Much easier to read, use, and implement info disseminated from WIDS less distraction.
- Getting Metars/sigmets/pireps does not easily give a good picture of projected weather it takes a lot less figuring to have the weather displayed on the scope.
- It is a lot easier to control traffic around visual aids compared to just trying to picture it in my head.
- I can make my own determination based on how I diagnose the wx on the WIDS/TCW. I prefer that.
- The TMU didn't have enough info. The WIDS was very easy to access info when needed.
- You are able to see the movement of the storm and anticipate its direction.
- None/Don’t know - 4

Which method of providing/receiving weather information do you prefer: WIDS, weather on TCW, or information form supervisor/TMU? Please explain why you like the method.

- WIDS. The information is instantly available, but does not interfere with the traffic display so there is less chance of traffic being affected by my need for information.
- WIDS - much easier to read, use, and implement info disseminated from WIDS less distraction.
- TCW, because there is less thinking involved to correlate the information to aircraft position. You can bring up the wx loop and easily determine a good heading. This reduces workload by not having to issue multiple vectors.
- I like both the WIDS and TCW. TCW - for the 6 level precip and WIDS - to not clutter up the scope for the extra stuff.
- TCW, I don't have to divert my attention too far from the traffic. I like the overlay. In my facility, there would be no room to install a WIDS anyhow.
- WIDS or TCW, because you are not distracted from your scope area.

- TCW. It gives me all the info I need. I can maximize the amount of info or minimize it. It’s all right where I need to look, on the radar screen!
- TCW with more information from the WIDS!
- WIDS - Separate from TCW for ITWS. Level 6 on TCW
- WIDS. It had the best display. Most options available. I did not like looking up to WIDS scope.
- WIDS eyes less time off the scope.

-

Appendix C

Weather Advisories for WS 1

SIMULATION TIME - 00:00:00

METAR 2355Z 02015KT 10SM VCTS SCT030 BKN035 OVC150 30/24 A2995

AIRMET
ZGN CWA 102 VALID UNTIL 010100
FROM 20W WVA TO SGF TO WST TO SWT
SCT TSRA MOV FM 28030KT...TOPS FL270-370.
SEE CONVECTIVE SIGMET 66E

SIGMET 66E
VALID UNTIL 0155Z
NY PA MD
WVA TO 15E SWT TO 15S WST TO 20NE ILL TO WVA
AREA SEV TS MOV FROM 27030KT. TOPS TO FL420.
HAIL TO 1 IN...WIND GUSTS TO 50KT POSS.

RVR

Runway = 05	6000+
Runway = 36L	6000+
Runway = 36R	6000+

SIMULATION TIME - 00:20:00

SPECI 0020Z 03018G28KT 3SM TSRA BKN027 OVC150 30/24 A2993
Lightning Warning

SIMULATION TIME - 00:35:00

SPECI 0035Z 33015KT 1SM TSRA BKN030 30/24 A2991
Lightning Warning

SIMULATION TIME - 00:40:00

SPECI 0040Z 33010KT 4SM RA BKN035 30/24 A2992

Appendix D

Weather Advisories for WS 2

SIMULATION TIME - 00:00:00

SIGMET 3E
VALID UNTIL 010200Z
OH PA NY ID
LINE 70NM EITHER SIDE NTH TO SWT.
AREA SEV TS MOV FROM 29030KT.
TOPS ABV 500. HAIL TO 2 IN. WINDS TO 55KT POSS.

METAR 2355Z 35010KT 15SM SCT020 BKN045 OVC150 30/24 A2995

Runway = 05 6000+
Runway = 36L 6000+
Runway = 36R 6000+

SIMULATION TIME - 00:19:00

SPECI 0019Z 35012KT 6SM VCTSRA- BKN020 OVC040 30/24 A2992 RMK PRESFR
Lightning Warning

SIMULATION TIME - 00:45:00

Runway = 05 4500
Runway = 36L 4500
Runway = 36R 3000

SIMULATION TIME - 00:46:00

SPECI 0047Z 36018G28KT 4SM TSRA OVC018 30/24 A2989 RMK PRESFR
Lightning Warning

Appendix E

Computational Procedure for Contrast Analysis.

For basic analyses of one-pattern repeated-measures hypotheses, we begin with a within-person assessment of the degree to which each participant exhibits the expected pattern of results (i.e., whether their scores follow the direction of the a priori hypothesis). First, we create a set of contrast weights, or lambdas ($\lambda_p s$), that represent the expected pattern of results. This can be done in a two-step procedure where we first identify the pattern of scores for each condition that might be expected if our hypothesis is correct. As an example, we can use a hypothetical measure of controller efficiency where our expected values range from 0 to 40. Our hypothesis is that these values will increase if we provide advanced weather information to the controller. However, our hypothesis is neutral regarding an efficiency difference in the measures between the WIDS and the TCW conditions, both of which provide advanced weather information. Given our hypothesis, we might predict our expected values for the WIDS, TCW, and Control conditions to be 33, 33, and 21, respectively, reflecting our hypothesis of greater values for the two conditions with advanced weather information.[2] We then subtract the mean of these expected scores ([33+33+21]/3 = 29) from each expected score (33-29 = 4, 33-29 = 4, 21-29 = -8) to yield the contrast weights of 4, 4, and -8. These weights reflect the predicted pattern of results. They also follow the basic requirement for contrast weights that the sum of the weights equals zero (4+4+[-8] = 0). Usually, contrast weights are then adjusted using one of two methods. For method one, the contrast weights are adjusted by dividing each weight by the greatest common factor (4), resulting in weights of 1, 1, and -2. For method two, the constraint imposed is that the sum of the squared weights is equal to 1, resulting in weights of .5, .5, and -1 (Masson & Loftus, 2003). For our analyses, we will use method two.

Next, we compute an *L* score (*L*p) for each controller that reflects the degree to which the controller follows the expected pattern of results. The *L*p score is the product of each controller's observed score under the condition at time t and the contrast weight associated with this condition at time t. We then sum the products using the following equation:

$$L_{\mathrm{Pi}} = \sum_{t=1}^{n_t} \lambda_{\mathrm{P}t} X_{\mathrm{it}}$$

where X_{it} is controller i's observed condition score, λpt is the lambda weight of the pattern for the condition at time t, and *L*pi is the controller i's *L*p score. This *L* score is a point estimate for the contrast and the average of all controllers' *L*p scores is our best estimator of the population value of the contrast. For our hypothetical example, we have controller i's *L*p score ([4 x 30] + [4 x 30] + [-8 x 20] = 80). Because controller i's *L*p score is positive, the observed data match our expected pattern of data. If controller i's *L*p score had been negative, it would indicate that the observed pattern of data was in the opposite direction of the expected pattern of results. The size of the *L*p score reflects the degree to which the controller's data match our predicted pattern of result.

We then compute a one-sample *t* test based on the sample L_p scores (in the following, we will only assume a sample of L_p scores without presenting hypothetical data since it is not necessary for the presentation):

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[2] This method should result in the same set of contrast weights for any set of expected values following the same pattern.

$$t = \frac{\bar{L}_{\mathrm{p}}}{\sqrt{\frac{s^2_{L\mathrm{p}}}{n_i}}}$$

where $\bar{L}_{\mathrm{p}}$ and $s^2_{L\mathrm{p}}$ are the mean and variance for all n_{i} controllers.

Next we compute a measure of effect size. Although there are many measures of effect size (Cohen’s *d,* Hedges' *g,* r^2, η^2, ω^2, and $\hat{\varepsilon}^2$, see Olejnik and Algina, 2000, for a discussion), we have chosen to use r_{contrast} as our primary measure of effect size because of its suitability for repeated-measures designs (Rosnow & Rosenthal, 2003; Rosnow, Rosenthal, & Rubin, 2000). It is relatively simple to compute r_{contrast}:

$$r_{\text{contrast}} = \sqrt{\frac{t^2}{t^2 + df}}$$

where $df = n_{\mathrm{i}} - 1$.

In cases where more than one planned contrast is of interest, we need to correct for conducting multiple tests on the same pool of data using a Bonferroni correction. For example, if we run five contrasts and want to maintain a Family Wise Error (FWE) of .05 then each contrast needs to be tested at the .01 level (.05/5).

We also compute a confidence interval (*CI*) around the $\bar{L}$ scores. It is important to understand how to interpret a *CI*. A 95% *CI* tells us that if we run the same experiment 100 times, 95% of the time the population mean (μ) will fall within the *CI* (Tryon, 2001). *CI*s provide information on power, where smaller *CI*s indicate higher power. To calculate a *CI* for 1-α we use the formula:

$$\mathrm{CI} = \bar{L} \pm \mathrm{t}_{\mathrm{N-1},\alpha/2} \frac{s}{\sqrt{N}}$$

where $\bar{L}$ is the average of all L_{p} scores, N is the number of L_{p} scores, s is the standard deviation of the L_{p} scores, and $t_{N-1,\alpha/2}$ is the critical t value for a two-tailed test of α.

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Appendix F

Calculation of Eye Fixations

The Research, Development, and Human Factors Laboratory uses the Applied Sciences Laboratory Model 5000 oculometer to collect visual scanning data from participants in air traffic control experiments. Although many measures can be obtained, the primary measures are the number and duration of fixations in defined scene planes, such as the radar display and the keyboard. The system measures both eye and head movement at a rate of 60 times a second (16.67 msec) to record points of gaze (POG) in x, y, and z coordinates relative to the scene plane. Visual angle is determined by the distance between POGs on the scene plane (x, y) and the distance between the observer's head and the scene plane (z). The eye tracker analysis software uses the visual-angle-based algorithm to identify fixations and define their durations.

The algorithm assesses the first 10 points in a POG recording file. It conducts point-by-point comparisons to determine when a saccade or a fixation has occurred. It compares the first recorded POG point (A) to the next point (B) and determines if B is within one degree of visual angle of A. If the pair is separated by more than one degree of visual angle, the second point in the pair is considered an outlier and the primary point (A) is compared to the next point in the sequence (C). If three consecutive points are outside one degree of visual angle of A, then the algorithm determines that it is tracking a saccade that includes points A and B. It then continues to track that saccade at point B, which becomes point A in the assessment process, and continues to search for a fixation. The algorithm also keeps a running total of the number of outliers during its search for a fixation. If the algorithm identifies four nonconsecutive outliers (e.g., B, C, E, F) out of the 10 points in the sample set, the first outlier (e.g., point B) becomes point A and a new search for the start of a fixation begins.

The algorithm determines that a fixation has occurred when five positive comparisons (between six points) are made without finding three consecutive or four non-consecutive outliers. In the simplest case, a fixation is identified when the first six points in the 10-point set meet this criterion (AB, BC, CD, DE, EF). The minimum fixation duration is, therefore, 100 msec. After the algorithm determines that a fixation is being tracked, it continues to determine if successive points are within one degree of visual angle of the most recently added point (e.g., G within one degree of F, H within one degree of G, etc.). The algorithm adds each of these points to the fixation until it finds three consecutive outliers, indicating that a saccade has been initiated. The algorithm then resumes the process of searching for the start of the next fixation.

Because parts of the radar scope scene plane are dynamic (e.g., moving aircraft symbols and data blocks), the algorithm is designed to track moving or sliding fixations. Sliding fixations occur when the first and last POG recordings span a visual angle greater than one degree as illustrated in Figure F1. In the example, points A and B are within one degree of visual angle, but point C is an outlier. The next comparison, between points B and D, is within one degree, as are comparisons between D and E, and E and F. Point G is an outlier, but the comparison between F and H is within one degree of visual angle resulting in the fifth positive comparison. The algorithm therefore determines that a fixation has started at point A and includes points A through H. It then compares point I to H. Since I is within one degree of H, it adds that point to the fixation. Point J is also added because it is within one degree of I. Although points F through J are more than one degree of visual angle from the start point of the defined fixation (A), they are still part of that fixation that is sliding from left to right and slightly downward across the scene plane. The algorithm continues to add points to the fixation until it finds three consecutive outliers, indicating that a saccade has started.

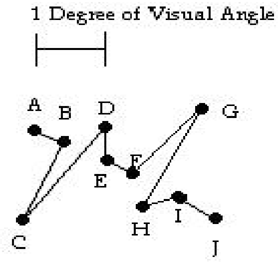

Figure F1. An example of a sliding fixation.