UNIVERSITY OF OKLAHOMA

GRADUATE COLLEGE

EFFECT OF AGE OF RADAR INFORMATION ON PILOT'S WEATHER RELATED JUDGMENT

A DISSERATION

SUBMITTED TO THE GRADUATE FACULTY

in partial fulfillment of the requirements for the

Degree of

DOCTOR OF PHILOSOPHY

By

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Norman, Oklahoma
2014

EFFECT OF AGE OF RADAR INFORMATION ON PILOT'S WEATHER RELATED JUDGMENT

A DISSERTATION APPROVED FOR THE
SCHOOL OF INDUSTRIAL AND SYSTEMS ENGINEERING

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ACKNOWLEDGEMENTS

I am very grateful to my advisors Dr. Chen Ling and Dr. Ricky Thomas for their steering me through the academic journey at University of Oklahoma.

I owe my deeply thanks to the other members of my doctoral committee: Dr. Randa L. Shehab, Dr. Dennis Beringer, Dr. Scott Gronlund, Dr. Theodore B. Trafalis for their big helps, important suggestions, and invaluable encouragements in my Ph. D study, dissertation writing and defense.

Dr. Jing Xing is gratefully thanked for her very valuable suggestions and great helps.

I thank Mr. David McClurkin and Ms. Julie Orrick for their supporting me in the data collection stage.

I would like to dedicate this dissertation to my husband, Guoqing Ge and my son, Justin Ge. My husband and my son accompany me through the tough time and many challenges in my Ph. D study here.

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ABSTRACT

Aeronautical data links that provided integrated information for long-term strategic planning and short-term decision aids in the cockpit will dominate future air-to-ground communications. However, data-linked weather information can be more than 14 minutes old by the time they reach the cockpit for use by pilots. The National Transportation Safety Board issued a warning that delayed radar information resulted in two fatal accidents. The reasons had been summarized as follows: pilots may not have been fully aware of the delay, and pilots treated radar information as real time and used it for tactical decision-making. Few studies have focused on how pilots interpreted delayed radar information. This study consisted of two experiments that contributed to three objectives: to develop an intuitive way to inform pilots of the delays and enhance their time awareness; to understand how pilots process delayed information and maintain spatial awareness; to objectively measures three stages of weather situation awareness.

The first experiment evaluated the effects of three types of time-stamp representation methodologies on participants' accuracy for quick assessments of the delay of NEXRAD mosaic radar images. "Direct age", "clock" and "UTC" timestamps were investigated with short, medium, and long levels of delay. Twenty-one participants compared two radar images, via their timestamps, to determine which one was more recent. The results indicated that "direct age" timestamp led to the highest accuracy and fastest response time, and was considered intuitive and easy to perceive by participants.

The second experiment contained three steps to evaluate the effect of time delay on distance estimation performance. These three steps represented the current understanding and projection stage of weather situation awareness. 30 student pilots completed the task, current and future proximity estimation to the storm cells based on the amount of time delay and movement speed. As expected, delayed radar information affected the pilots' proximity judgments and deteriorated their weather situation awareness. In the first step, the participants overestimated the current location of the storm cell when the time delay was below 10-mins and storm-cell movement was less than 50 knots. In the second step, the participants underestimated the current distance between the aircraft and storm cells. In the third step, the participants overestimated the future distance when the time delay was long and the movement speed was fast. Participants used a conservative way to estimate the distance. Pilots could be trained to use delayed weather information to enhance spatial awareness, to make tactical decisions, to estimate current position of storm cell, and plan to avoid potential hazards.

Chapter 1 Introduction

1.1 Pilot's Weather related Decision Making

Hazardous weather is one major contributor to fatal aviation accidents (Latorell & Chamberlain, 2002), such as convective weather, winter weather (e.g., snow and ice storm) and non-precipitation (e.g., strong winds and dense fog). Convective weather particularly affects general aviation because of the rapid change of weather conditions including: heavy rain, severe turbulence, high winds and gusts, severe downdrafts and microbursts, or instrument meteorological condition (IMC). Lightning can destroy electronic devices such as navigation equipment and radio. Turbulence from winds associated with thunderstorms can kill passengers and aircrew. Turbulence can literally rip off the wings of the airplane. A survey of general aviation (GA) accidents, from 1982 to 1993, revealed that 66% of fatal accidents resulted from thunderstorm (Chamberlain & Latorell, 2001).

Pilots are responsible for avoiding hazardous weather conditions by using appropriate weather information. Because the position of the plane and weather conditions are continuously changing, pilots must be regularly updated regarding weather information, remain knowledgeable about the environment, and make correct judgments. Failure to obtain the most current information or deviate around weather can put the flight into a dangerous position.

According to a National Transportation Safety Board report, some weather-related accidents stemmed from pilots' decision error and poor judgment (NTSB, 2006).

For example, pilots decided to continue a Visual Flight Rule (VFR) flight into IMC (Capobianco & Lee, 2001) or attempt to land without recognizing the hazard. In some cases, these actions were intentional or unintentional violations of safety rules and misinterpretation of weather information. In other cases, pilots may be overconfident in their personal abilities and underestimate the risk (Narinder Taneja, 2002). Poor judgment by a pilot may be due to incorrect or unambiguous weather information, or inexperience with flying in local weather conditions, or identifying marginal weather conditions (Burian et al., 2000; NTSB, 2006). One or a combination of these factors may result in the pilot being unaware of the deteriorating weather conditions, failing to correctly recognize the level of the hazard, or miscalculating their positon relative to the hazardous areas of the storm (Novacek, et al., 2001).

Weather information is crucial for pilots; therefore it was mandated in terms of source, format, validity and geographic orientation (Lindholm, 2010). Pilots can direct query Flight Service Station (FSS), En Route Flight Advisory Service (EFAS, or "Flight Watch"), and Air Traffic Control (ATC) personnel. Pilots also can tune into automated weather information services such as HIWAS, AWOS/ASOS, and ATIS (Chamberlain & Latorella, 2001). However, sometimes information from these sources is limited, and when weather is a problem, the frequencies used to obtain this information become saturated, making this information inaccessible. Today's aviation weather information is data rich since it provides alphanumeric (includes icon or symbol) and textual description, verbal communication, and graphical images over a much larger geographic area than needed. The complete and usable weather information could benefit pilots' situation awareness, decision-making, and safety (Chamberlain & Latorella, 2001).

Many studies focused on how to effectively display different weather information. William (1999) compared the weather textual description and graphical weather information, and showed that pilots preferred to the graphical information. The study by Coyne et al. (2005) showed that the graphical METAR information, effectively improved pilots' weather judgment, relative to judgments made when using only textual METAR. Lindholm (2010) explained that the graphics could transmit more information than text, color and other formats. The graphical information also matches the mental model structure of users and aids in decision-making. Graphical presentation made pilots become more confident to make better go/no go decisions (Novacek, et al., 2001). Chamberlain and Latorella (2001) suggested that graphical weather information is an appropriate representation that can be effectively integrated with other information (e.g., terrain, symbols). However, we need to consider the color coding, symbol design and overlay issues inherent to graphical display (Graz et al., 2008).

Voice-based and analog communication systems that transmit text and verbal information have an inefficient nature that contributes to the saturated communication capacity. Pilots may have to wait minutes to receive in-flight weather briefings due to busy signals and receive it in abbreviated speech and text reports that further hinder their understanding of the weather-related threats. The availability of digital data link communication as well as advanced graphic display will fill this gap and ensure that adequate and useful weather information will be on hand for the pilots. Future air-to-ground communications will be dominated by various forms of aeronautical data link (text, graphics and digitized voice), which will provide the pilot with integrated information for long-term strategic planning and short-term decision aids (Stough et al., 2000).

Data link, by definition, is the transfer of digitized information (Air/Ground). There are a series of networks in the air and on the ground where aircraft can broadcast a three-dimensional position to each other and to on-ground Air Traffic Control (ATC) using a digital format. In the mid-1990s, the Federal Aviation Administration (FAA) introduced digital data-link communication as a means of exchanging information between aircraft and ground base (Kerns, 1991). In 1992, the FAA organized the Data-Link Operational Requirements Team (DLORT) and gave it the responsibility to develop an operational concept for the introduction of digital data-link communications in the National Airspace System (NAS). The DLORT selected several individual services for nationwide implementation between 1996 and 2000 including: Basic Air Traffic Management Services, Basic Text Weather Products, Automatic Downlink of Pilot Weather Reports Traffic Information, and Weather Graphics.

The first application of data link, Graphic Weather Service (GWS), was to display graphic information in the cockpit (Lind et al., 1994). The first weather graphics product operated by GWS was weather radar images that transmitted to the requesting aircraft via data link. A compression algorithm for radar images was developed that formed the basis for the GWS. With GWS, routing air traffic control (ATC) and weather (WX) messages were exchanged between the ground and aircraft. The presentation of weather and ATC information on the display is the main interface between pilots and data-link. Pilots could make informed decisions regarding the needs for deviation and their confidence and effectiveness was markedly increased. Compared with data-linked radar images, the current voice communication had frequent errors, such as miscommunication and misunderstanding (Rehmann, 1995).

1.2 Data-linked radar information

Today's cockpit data-link weather displays give pilots an unprecedented quantity of weather information (Stough et al., 2000). Advanced weather display via data-link in the cockpit could provide significant advances in aviation safety (Novacek, et al., 2001). However, the quality of the information depends heavily on updating rate, resolution and coverage area. Studies (Novacek, et al. 2001; Beringer & Ball, 2003) have shown that radar resolution affects pilots' judgment. A fair amount of data was treated before the images reach the satellite receiver. So, sometimes the images will not have right resolution and lose real features. For example, data-linked radar images from Weather Services International (WSI) or through XM-based WxWorx are not the same as the images found on the National Weather Service (NWS) website because of the different resolution.

Radar information has proved to be extremely valuable for the pilot to navigate the proximity to storm cells (Wu et al., 2011) and to avoid threatening weather. For instance, pilots need to decide by using radar information whether to penetrate a hole in a line of storm cells. The on-board weather radar is critical for the pilots to monitor the tactical weather conditions in real time. However, Next Generation Radar (NEXRAD) could provide an excellent strategic view of the weather situation to satisfy the growing demand (Kelly et al., 2000). The NEXRAD incorporated a number of improvements over the radar systems previously in use. It provided improved resolution and sensitivity, allowing operators to see thunderstorms, gust fronts and meso-scale features of thunderstorms that were not visible on radar. NEXRAD also had a much increased range allowing detection of weather features at much greater distances from the radar and on-board radar.

NEXRAD is the standard reference for the NWS's Doppler radar network. A completed scan from each of the active NEXRAD radars is collected and integrated into a national grid, manually inspected and refined by meteorologists, then instantaneously up-linked and distributed via satellite to users. In total, the process takes about 5 minutes (Wu et al., 2011). One early implementation of up-linked radar mosaic, GWIS, developed at MIT Lincoln Lab, had a 15-minute update rate (Chandra et al., 1995). With greater computing capability, increased observation density, the update frequency of data-link will increase to better meet the needs of pilots. Because of increased update frequency, the users can expect more frequent forecasts based on updated data, and receive potentially better aids for decision making during preflight and en-route operations. High resolution NEXRAD from XM WX is composed of any precipitation exceeding 10dBZ in intensity, and incorporates multiple radar elevations for an accurate look at conditions relevant to users in the air, at sea, and on the ground. The update frequency is 5 minutes.

The time delay means that radar information is several minutes old and not real time. The NEXRAD "age-indicator" on the cockpit display indicated the time that the mosaic image was created, which meant the NEXRAD image was always older than the actual weather conditions. The NTSB (2011) issued a safety alert to warn pilots using in-cockpit FIS-B and satellite weather display systems that the NEXRAD "age indicator" can be misleading. The actual NEXRAD data can be as much as 20 minutes older than the age indication on the display in the cockpit. If misinterpreted, this difference in time can present potentially serious safety hazards to aircraft operating in the vicinity of rapidly moving and developing weather systems.

Two fatal accidents happened near the quickly developing and fast-moving convective weather because of the delayed radar information. In the death of one pilot in Brownsville, Tennessee on March 25, 2010, the pilot's cockpit display indicated that it had received a one-minute-old NEXRAD image that was delivered halfway through the flight. The image indicated that severe weather was about seven miles away from the home base where the pilot was attempting to land. However, since the information was five minutes old, the severe weather was actually just crossing over the home base at about the time the display received the NEXRAD image. In the death of another pilot traveling near Bryon, Texas on Dec. 19, 2011, the pilot was diverting to avoid weather and had likely received several NEXRAD updates in the minutes leading up to the accident. Post-accident reviews revealed that the NEXRAD data received by the pilots likely would have led him to believe that he was flying clear of precipitation along the edge of the rain. Near the end of the flight, the pilot flew into a section of the developing rain shower, while his display likely indicated that he still remained clear of the precipitation.

The study of Burgess and Thomas (2004) had already suggested that delayed radar information would lead to noticeable errors in estimating the proximity to severe weather area and the speed of storm cells movement. Few studies have focused on the effect of delayed weather information. Chamberlain and Latorella (2001) noted that using delayed weather information is important for pilots to keep a safe distance between their aircraft and any en route weather. However, it is not clear whether pilots could keep safe distances from delayed data. Furthermore, Latorella and Chamberlain (2002) questioned whether pilots could estimate the current position of storm cell, perceive danger, and plan to avoid potential hazards using delayed data. Yuchnovicz et al (2001) also were concerned that pilots will try to extrapolate the storm cells and decide whether to avoid areas of perceived danger or plan a long-term route to avoid potential hazards.

In summary, data-link technology is developing and many weather systems have integrated radar and other information into the cockpit to support decision making. Data-linked radar information is crucial in the cockpit although it is delayed. However, delayed radar information could result in fatal accidents (NTSB, 2011). The novelty of the current study lies in the fact that the time delay issue is considered into the pilot's judgment related to the weather conditions, and tries to investigate whether pilots could use delayed radar information to estimate current position of storm cell or project into future weather conditions.

1.3 Organization

The structure of the dissertation is presented as follows. Chapter 2 provided a review of the theories related to information processing and situation awareness. Based on the review, the conceptual model was built for delayed weather information processing. Chapter 3 described previous studies of delayed information. Chapter 4 described pilot's task analysis and we explained the reasons for designing three experiments. Chapter 5 introduced the first experiment, timestamp representation for the delayed information. Chapter 6 introduced the second experiment including an investigation of the effect of delayed information on the three stages of weather situation awareness, current location estimation of thunder storms, current distance between aircrafts and storms, and future distance between aircrafts and storms. Chapter 7 provided the discussion of the results and presented needs for further study.

Chapter 2 Model of Information Integration and Situation Awareness

In recent years, more advanced weather information systems were introduced into the cockpit containing more than twenty types of weather information (such as WxWork, WSI). Regardless of the weather systems, the radar images are essential for the pilots. Bass and Minsk (2001) developed the Weather Hazards Integrated Display System (WHIDS). Rather than showing all weather data to pilots, the WHIDS, which is a pilot-centered system, enabled pilots to decide what weather information should be displayed. The weather products in the WHIDS included Terminal Aerodrome Forecast (TAF), Radar, freezing levels, METARs, pilot weather reports (PIREPs), satellite images, and significant meteorological information (SIGMET). Spirkovaska and Lodha (2002) presented another system, the Aviation Weather Environment (AWE) system that provided intuitive graphic presentation for aviation-specific weather information that was extracted from textual documents describing meteorological observations and terminal area forecast that were linked to the flight path and schedule. Pilots can interact with the system so that it only displayed information they currently needed. Whereas, the WHIDS organized the weather information based on information priorities.

Data-linked weather information included three dimensions: time, location, content and pattern (color or format), which were continuously updated. We need to know when the information was issued, where the storm cell and aircraft were, and the severity level of weather in the area. Radar information is useful and relevant only if it describes the appropriate time period. The time period is usually known as the amount of time delay for the radar image or equivalent to the period between the issued time and the current time. For the content and pattern of weather information, studies focus on colors, icons and displays (Ware & Plumlee, 2013). An icon was shown when it was a good indication of a state variable that needs immediate attention, and a display was used to show the location and spatial extent of information.

Weather situation awareness is obtained from weather information that is supplied by many weather system products. The weather information carries a time dimension and spatial dimension so that weather situation awareness encompasses temporal and spatial awareness. Temporal weather awareness is important for both the diagnosis and the prevention of weather threats (Sarter & Woods, 1991).

Weather systems in the cockpit presented pilots with the integration of all types of delayed weather and navigational information about their overall situation. On the other hand, pilots still need to integrate data-linked information to maintain situation awareness and safety. Information integration theory and situation awareness are investigated to examine how pilots use delayed radar information to keep away from the hazardous weather area.

2.1 Information Integration theory

A general model of information processing includes three stages: perception, cognition, and decision making (Proctor & Zandt, 2008). In the perception stage, successful information extraction from the signal depends on whether the sensory input is clear and displayed for an adequate amount of time. In the cognitive stage, information extracted from stimulus could be identified, classified and processed for the goal of determining the appropriate response. The decision-making stage provides the final appropriate response and is at the core of the information processing.

When viewing a display, the user is required to integrate different types of information to maintain situational awareness. Based on the general information processing model, the information integration also could be summarized into three stages model: perceptual integration, cognition integration and integration for judgment. In the perception stage, the display should show all necessary information. In the cognition stage, the users need to integrate and process information shown on the display. The integrated display design should put related information together to reduce the mental integration efforts and help the cognition integration processing.

Proximity Compatibility Principle (PCP) (Barnett & Wickens, 1988; Andre & Wickens, 1990; Wickens & Carswell, 1995) was developed for the design of integrated information display. PCP has two dimensions of proximity or similarity: perceptual proximity (display proximity) and processing proximity (mental proximity) (Wickens & Carswell, 1995). Perceptual proximity defines how similar two types of task-related information can be. Processing proximity defines the integrated degree of two or more information sources in a task. Processing proximity is high if sources of information must be integrated during processing whereas the processing proximity is low if sources of information need to be processed independently. Perception and processing proximity are compatible: high processing proximity needs close perceptual proximity.

Wickens and Carswell (1995) listed six proximity manipulations that can be used to successfully apply the PCP and increase display proximity. These manipulations include spatial proximity, connections, source similarity, code homogeneity (same analog properties, i.e., length, orientation or brightness), and object integration and configuration.

The processing proximity corresponding to the cognition integration seems difficult in defining the degree of integration. Few studies have explicitly provided and described how to cognitively integrate information in the cognition stage. Cognitive integration represents the processing of information while the decision or judgment is the result of information processing. Investigation of the decision models aids in understanding cognition integration method or principle.

2.2 Information Integration - Judgment Theory

Judgment itself is the result of the integration of discrete items of information. Slovic and Lichtenstein (1971) summarized two types of judgment theory that focused on the cognitive structure of the judgment: the regression approach and the Bayesian approach. In the regression approach, the correlational paradigm describes the information integration by means of correlational statistics. It requires the users to make quantitative evaluations of a series of information, each piece of which is defined by one or more quantified dimensions. Brunswick's (1956) lens model showed that the relationship between cues, criterion values, and responses was indicated by the following regression equation:

$$Y = b_1 X_1 + b_2 X_2 + b_3 X_3 + \ldots\ldots$$

Where X is the stimuli; b is criteria; Y is the response. The extension of the regression approach is known as the integration theory (Anderson & Shanteau, 1970). Integration theory focuses on factorial design that scales the stimulus items and determines the weighing parameters. The integration refers to the composition rules in a simple algebraic model that involves adding, averaging, subtracting, or multiplying the stimulus items. In the composition rules, the additive model plays a key role in correlation and other complex rules. Bayes' approach is the multiplicative model that emphasizes the judgments or response criterion, showing the largest probability of occurrence.

The essential part of judgment is the integration of information processing by using different composition rules to build a relationship between a series of information cues. Appropriate selection of rules should be based on the complexity of the information. And sometimes, human judgment is often more complex than a simple algebraic model.

Situation Awareness (SA) is a product of the information processing model (Uhlarik & Comerford, 2002) or an internalized mental model of the current state of the system, which requires the operator to integrate all types of information into a whole picture (Endsley, 2001). This integrated picture forms the central organizing feature on which decision-making and actions are dependent.

2.3 Information Integration -Situation Awareness (SA)

There are different definitions of situation awareness depending on different focuses, such as information processing or information components. The most commonly cited is Endsley's definition, which is a product of the information processing model (Endsley, 1993, 1995a, 1995b, 1998, and 2000). The SA model includes three stages: perception (i.e., perception of elements in the environment), understanding (i.e., comprehension of the current situation), and prediction (i.e., projection of future status) (see Figure 2.1).

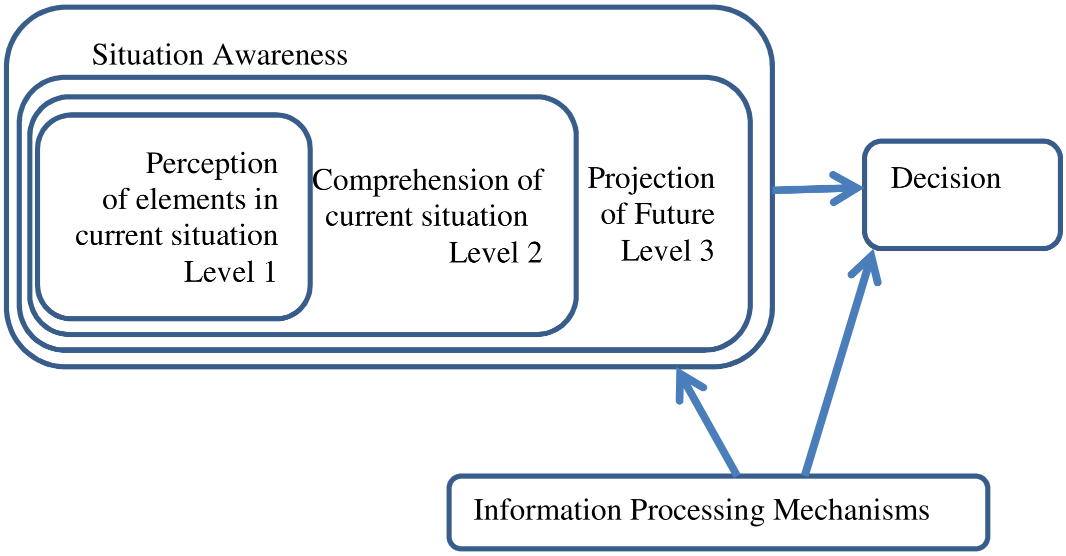


Figure 2.1 Part of model of situation awareness (Endsley, 1995b)

The key to form situation awareness is to group data and integrate information. This integration requires very unique combinations and portrayals of information. A set of SA-oriented design guidelines that stresses the integration are listed below (Endsley, 2001):

1) Low level data should be integrated, interpreted and presented directly for the need of high level SA.

2) Information on the display should be organized so that the information needed for a particular goal is co-located and directly answers the major decisions associated with the goal.

3) The display should provide an overview of the situation across the operator's goals at all times and enable efficient and timely goal switching and projection.

4) Critical cues that are very important and related to key features of a schema need to be determined and made salient in the interface design.

5) Extraneous information not related to SA needs should be removed.

6) Support for parallel processing, such as multi-modal displays, should be provided in data rich environments.

SA-oriented designs have been successfully applied to a wide variety of systems involving remote maintenance operations, medical systems and flexible manufacturing cells (Endsley, et al., 2003). In the aviation domain, there may be multiple definitions and types of SA for supporting different tasks and cognitive behaviors.

2.4 Situation Awareness Measurement

Measurement of situation awareness is valuable in the design since SA provides the primary basis for subsequent decision making and performance in complex and dynamic systems (Endsley, 1995a; Endsley & Garland, 2000). In the study, several measurement techniques were reviewed with an assessment of the advantages and disadvantages:

Physiological Technique, such as eye track: the advantage is to determine the level one information that could be registered into cognition; the disadvantage is that it cannot determine how much information goes into comprehension.

Performance measure: the advantage is that the measure is objective; the disadvantage is that it cannot explain why a poor performance occurred in a given situation or in level one, two, or three.

Subjective Techniques--- self-rating: the participants subjectively rate their own SA but are more likely to convey a measure of their confidence level, as it relates to their SA.

----Situation Awareness Rating Techniques (SART): rating a system design based on the amount of demand on attentional resources and understanding of the situation. SART is correlated with the performance measure.

-----observer-rating: using independent, knowledgeable observers to rate a subject's SA.

Questionnaires: directly measures SA and does not require subjects or observers to make judgments about situational knowledge on the basis of incomplete information.

---Posttest: detailed questionnaire after the completion of each simulated trial. However it is difficult for subjects to report the previous test and they tend to overgeneralize and over rationalize.

----Online: operators are asked about their SA while they are doing the simulated tasks. However, this technique is highly intrusive on the task.

----Freeze technique: simulation is frozen at randomly selected times and subjects are being queried about their perception of the situation at the time. The Situation Awareness Global Assessment Technique (SAGAT) is to assess SA across all of its elements based on a comprehensive assessment of operator SA requirements.

Endsley' s theory supports a validated measurement technique since SAGAT allows for objective assessment of SA by making comparisons of operator responses to knowledge questionnaires for the three levels of SA (perception, comprehension, and projection). SAGAT and SART are considered to be the two most widely used techniques. Endsley et al. (1998) suggested that SART was highly correlated with confidence level in SA.

Endsley (1995b) already considered the confidence level, an important aspect of situation awareness, concerning the degree of the uncertainty in the information and the accuracy of information processing. The relationship between confidence and SA showed that participants were typically more confident in their SA responses during the low rather than the high temporal and perceptual demand conditions (Lichacz, et al., 2003). Calibrating confidence should therefore be considered as an important element of future SA research.

SA should be measured using different tools by strategy to converge different results into the same direction (Van Dijk et al., 2011). Those tools together could provide a coherent picture of SA. The choice of a certain technique for measuring SA depends on the levels of SA. Because of the disadvantage of this performance measure, Uhlarik and Comerford (2002) suggested that SA measuring should: ensure concurrent validity; have a comfortable test environment; and be careful to suggest that SA is the cause of behavior changes.

2.5 Model of Information Integration and Situation Awareness for Pilots' Task

The weather information processing tasks of a pilot can be generically represented as a form of multi-cues information integration (Mosier & Kirlik, 2004). Maintaining an accurate understanding of the situation for pilots is based on the integration of several correlated cues in the cockpit. They spend much time during the flight maintaining and updating an accurate mental picture of where the aircraft is, whether to avoid a severe weather area or predicting if the weather conditions will affect the flight plan. The pilots' situation awareness forms the basis for decision-making during a flight. A loss of situation awareness is dangerous for the pilots (Edwards, Wickens & Moorman, 1991).

2.5.1 Pilots Situation Awareness

Fracker (1988) summarized the definitions of situation awareness of pilots from several studies and defined situation awareness as the pilot's knowledge that is from the focal region. The situation assessment that will predict the quality of SA depends on the knowledge stored in the pilots' long-term memory. This definition seems to be inadequate for aviation domains (Sarter & Woods, 1991) since it hasn't taken the temporal aspect into account.

According to Endsley et al (1998), situation awareness can be described in three hierarchical stages: in level one, the pilot needs to perceive information about the aircraft (airspeed, position, altitude, direction, etc.), weather, and other elements; in level two, based on a synthesis of disjointed level one elements, the pilot needs to integrate various data elements, and determine the impact of a change in one system's status on another, or deviation in one state from expected values; in level three, based on the comprehension that a storm cell is likely to create a hazard situation, pilots needs to decide diversion route or ascertain potential weather conflict. According to the definition of SA, the relationship of three stages of SA could be depicted as follows: weather information is shown on the display, which could support the information comprehension; furthermore, the combination of perception and comprehension could support the projection of future conditions. Therefore, if pilots are informed by displaying the present position, speed, flight path, and environmental variables such as temperature and wind, then they will know the present and project the future condition.

Based on the information processing model, the SA model has three levels focusing on the processing procedure. Depending upon what information was processed, Wickens (2002) divided pilot's SA into three components including: spatial awareness, system (mode) awareness, and task awareness. The concept of spatial awareness is inherent in the task of an aircraft flying through a 3-dimension space filled with other object hazards, such as other aircrafts and weather conditions. System awareness includes a pilot's comprehension of aircraft status and mode, which may affect pilot performance (e.g., automation mode awareness). Finally, task awareness relates to a pilot's knowledge of aviation control, navigation, and communication (with a co-pilot or air-traffic controller), and systems management (e.g., managing fuel, cabin pressure, electricity). Endsley (1999) described the needed SA elements for many types of aircraft systems as: spatial/temporal SA, environmental SA (weather situation awareness), and tactical SA.

2.5.2 Pilots Weather Situation Awareness

Endsley et al (1998) listed SA weather information requirements of commercial pilots: within level one, temperature, precipitation, visibility, ceiling, wind, direction and speed of storm movement, intensity and rate of change of intensity; within level two, timeliness of information, hazard level, potential thunderstorm, relative distance and bearing to weather area; within level three, projected hazard level, projected severity of hazardous weather, estimated time for weather to lift above minimum, projected escape routes.

Latorella and Chamberlain (2002) summarized weather situation awareness into the following categories: location and intensity of weather (SA level one), proximity and hazard level of the weather, and reliability of this information (SA level two), and projection of where the weather will be in the future, its intensity level and relevance to the mission at that time (SA level three). Under level two SA for aviation, weather information includes an understanding of how relevant existing weather is to the individual pilot, aircraft, and mission. Pilots must estimate the distance and bearing to the weather that is identified, and estimate the ramifications of its intensity, aircraft characteristics, and mission. Also pilots need to take the timeline into consideration by using old information.

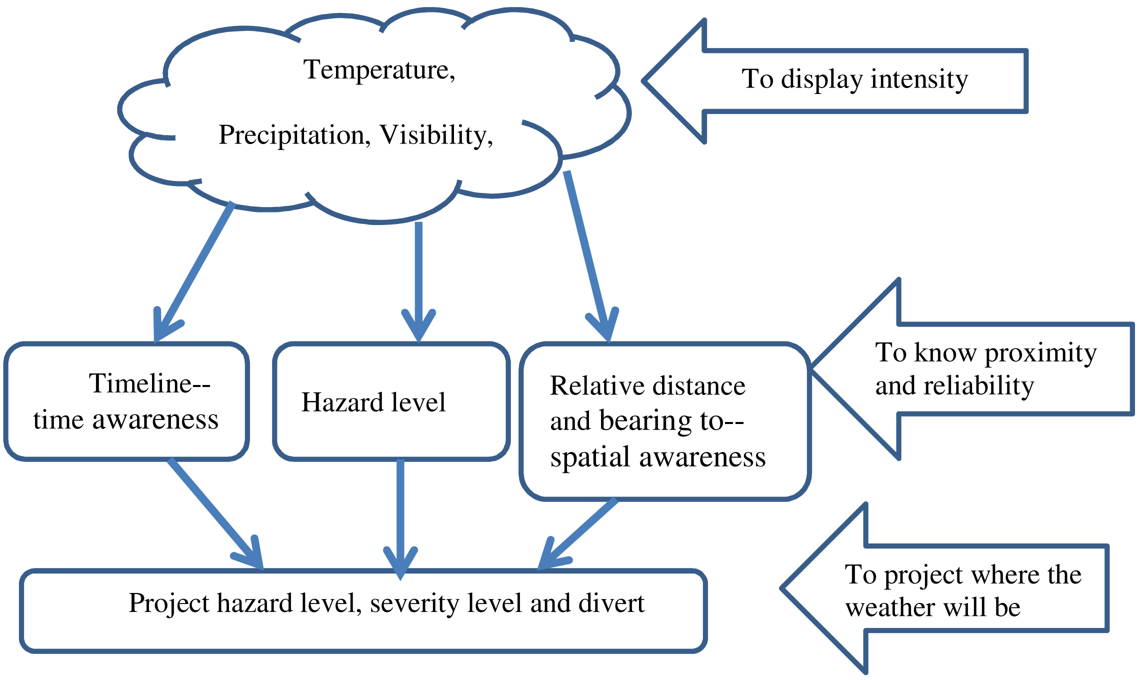


Figure 2.2 Summary of Weather situation awareness

(Endsley et al., 1998; Latorella & Chamberlin, 2002)

In Figure 2.2., the timeliness of information component is a very important part of level two and level three SA (Endsley & Garland, 2000). And the timeliness, temporal aspect of SA, associated with the perception of time and the temporal dynamics, formulate the SA. The perception of time needs to understand how much time is available for some actions to be taken or some events to occur. The dynamic aspect is another important temporal aspect of SA. The rate of information change regarding the current situation allows for projection of future situation. A situation dynamic nature also contains how far away some element is and how soon the elements have an impact on the task and goals.

Another component of weather situation awareness is spatial awareness, which includes knowledge of (a) attitude, (b) location relative to terrain, (c) waypoints (d) flight path vector, and (e) speed (Uhlarik & Comerford, 2002). According to Wickens (2002), spatial awareness is defined as the extent to which a pilot notices storm cell in the environment (Level 1), understands where these storm cells are with respect to own-ship (Level 2), and understands where these storm cells will be relative to own-ship in the future (Level 3).

For the measures of temporal and spatial aspects of weather situation awareness, we need to test the timeliness understanding, know the current location of storm cells and aircraft, and understand the relative location of storm and aircraft in the future. Bolton et al. (2006) stated that no studies have directly measured the three levels of spatial awareness: identification of terrain, its relative spatial location, and its relative temporal location.

The pilots' weather situation awareness is constrained by the degree of uncertainty and reliability of weather information, and time stress (Elgin & Thomas, 2004). Endsley (1999) listed a series of factors related to loss of situation awareness and conditions contributing to errors: visual illusions, poor knowledge/experience, over-projection current trends, and so on. Thus, Endsley (2000) concluded that there is no guarantee for the performance at certain levels of SA. It may be possible to occasionally perform well with a very low level of SA.

2.5.3 Pilot Weather Judgment

Judgment or decision making (JDM) was defined as a task characterized either by uncertainty of information or outcome (Pitz & Sachs, 1984). Judgments by pilots were separated into two types of mental processes: perceptual response and cognitive decision (Jensen, 1982). The common perceptual judgment includes: distance, altitude, and speed judgment. The cognitive judgments required amounts of relevant pieces of highly probabilistic information to make a choice. Madhavan and Lacson (2006) try to understand the pilots' judgment and decision when encountering severe weather conditions. Based on the previous studies, the judgment process that decides to continue VFR flight into IMC involved multiple stages:

a) Problem vigil----can detect the appearance change of dark cloud
b) Recognition----can recognize the developing dark cloud that indicates a potential thunderstorm

c) Diagnosis----understand and assess the possibility that cloud development could lead to a potentially dangerous storm and its implication for flight.
d) Alternative identification----identify various alternative flight path.
e) Risk assessment----try to determine the risks associated with the alternatives.
f) Background factors----personal and social pressure influence the decisions
g) Decision-making pilots choose the final course of action (continue to fly or divert)
h) Action----move flight controls

Based on those stages, the task components can be further classified into three categories: information acquisition, situation assessment, and choice of action.

During the information and the situation assessment stage, the uncertainty of information will result in the unreliable information display and uncertain situations, which is difficult to justify so that people tend to avoid making a judgment (Elgin & Thomas, 2004). The uncertainty of information can be spatial or temporal uncertainty. At this point, pilots' weather judgment is the result of weather situation awareness. Spatial uncertainty refers to the resolution of display and to the display lacking the scalar information (Yachonovica et al., 2001). Temporal uncertainty is the uncertain rate of information update. Timestamp do not show the exact age of radar information, which makes it difficult for pilots to predict the storm's position relative to the last update and project the storm's path.

The updated data are not real time so pilots only use it to make strategic plans, such as plan a safe flight path or long-term responses. Tactical operations required quick, reactive responses and short-lived actions (Elgin & Thomas, 2004). Latorella and

Chamberlain (2002) gave the general definition for the strategic and tactic action as follows: strategic action--- plan, think, evaluate, anticipate, and project; tactical action-- respond, act, do, fly, avoid, and maneuver. Three behavioral modes covered these actions: a) amount of time available, b) amount of experience and attention needed for the task, c) the degree of knowledge-based processing used. The relative location is the most salient cue for tactical/strategic distinction in IMC condition while estimation of distance from the convective weather is most important for the strategic plan.

However, Coyne, Baldwin and Latorella (2008) denoted that pilots have difficulty in estimating weather conditions and tending to overestimate weather condition, that is, the estimated weather condition is better than actual condition. New technology with good display design may improve the estimation and judgment. Latorella and Chamberlain (2002) suggested that showing storm intensity, proximity to weather (storm location and aircraft location), having weather radar, range rings, and arrows on cells (indications of cell movement) etc. on the display supported tactical use of weather products.

2.5.4 Model of Weather Situation Awareness and Information Integration

Grounded on the model of information integration theory and SA, we build the weather information integration and situation awareness model for pilots' task in the cockpit. In the three stages of weather information processing model, the first step is to display storm speed, direction, and timeline to let pilots know the location of the storm as a function of time. In the second step, pilots integrate speed, direction and time etc. information to understand the current relative distance between the storm and aircraft and have good spatial awareness and time awareness. Based on the time awareness and spatial awareness, pilots could project future condition between the storm and aircraft, and make weather judgments for the future flight plan (see Figure 2.3).

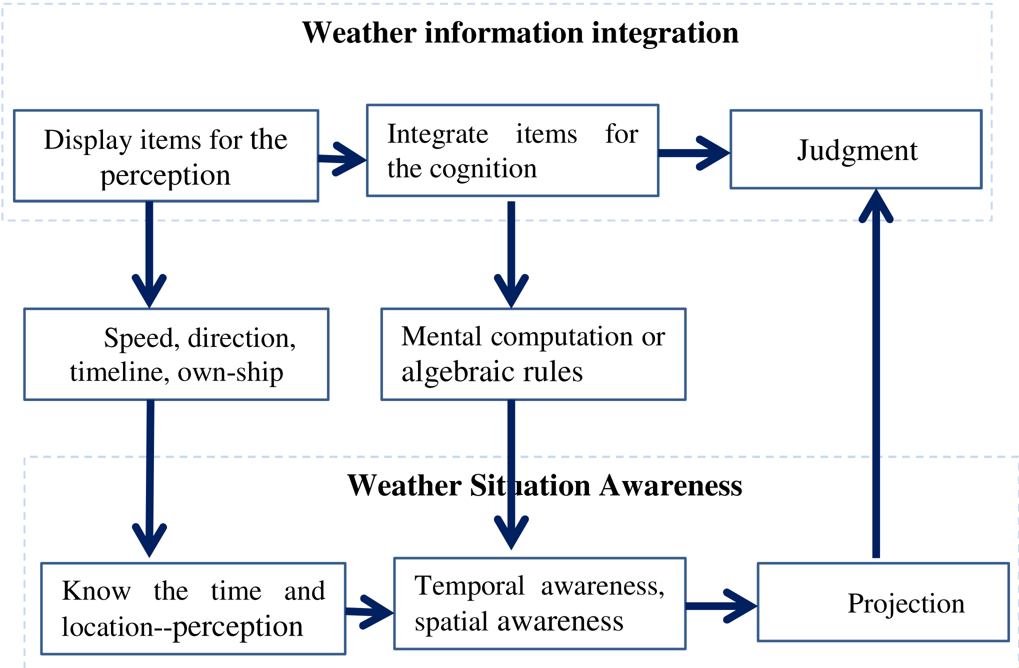


Figure 2.3 Model of weather situation awareness and information integration

Using this model, we try to analyze how pilots process the data-linked radar information supplied by those weather systems. The goal is to investigate whether delayed weather information could support pilot's time awareness and spatial awareness and help pilots make tactical decision and accurate proximity estimation. The time awareness and spatial awareness may yield uncertain time and spatial estimation.

Chapter 3 Previous Study of Delayed Weather Information

Madhavan and Lacson (2006) summarized the benefits and limitation of data-linked weather information. The benefits include the reduction of demands on working memory as well as the needs of accurate real time data that may be difficult to collect. The visual information allows pilots to make quick decision, such as choices of action without spending much time in the decision making, which is particularly critical in time-pressured situations or in rapidly deteriorating weather condition. Limitations associated with data-linked data include sense of distortion and information clutter. However, they ignored the time delay issue. The NTSB (2011) warned that the amount of time delay could be 15 to 20 minutes.

Even small amount of time delay can be important for the safety of flight, especially when considering fast-moving weather hazards, quickly developing weather scenarios, and/or fast-moving aircraft. NTSB (2011) recently investigated two fatal accidents where in-cockpit NEXRAD mosaic imagery was available to pilots operating near quickly developing and fast-moving convective weather.

The two accidents may have resulted from the wrong age indicator on the radar image that led to inaccurate proximity estimation to the severe weather area (NTSB, 2011). The age indicator on the radar image did not show the real amount of time delay of the radar information. Even though the age indicator showed the actual time delay, pilots seem to only have four minutes or seven miles space to avoid the severe weather area, which is not enough for them make a diversion. And they used the delayed information for the tactical decision. Why did they not plan to take action 10 or more minutes ahead so that they wouldn't be affected by the amount of time delay (see Figure 3.1)? The answer may be that pilots might become overconfident in their ability to determine where it is safe or unsafe based on the delayed information. From this information, they make a tactical decision that could be extremely dangerous (Burgess & Thomas, 2004). We still need to know the previous studies on the other problems associated with delayed radar information.

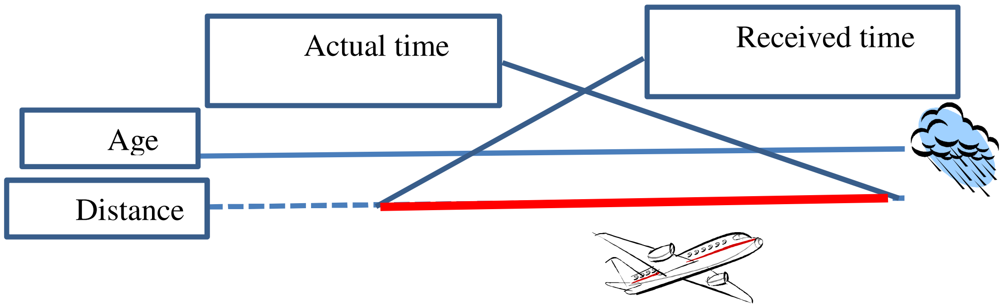


Figure 3.1 Timeline of the delayed information

A particularly relevant study undertaken at the Lincoln Laboratory of MIT (Lind, et. al., 1994) provided a valuable first step by looking at the effect of data-linked graphical weather on pilot's decision making. When compared to strictly text information, the graphical information caused pilots to become more confident in their assessment of the weather, and to make better go/no go as well as flight path change decisions. Beringer and Ball (2004) demonstrated that pilots will be over confident to believe that they know their exact position relative to hazards and assume that the flight can go through these hazards. Chamberlain and Latorella (2001) presented that such over-confidence combined with a lack of sense of the age of information could have dire consequences. For example, using delayed radar information, it is difficult to know that a “gap” in a quickly moving cells line is now filled with another cell.

Over-confidence could be one issue due to the use of data-linked graphic weather information. The time-delay issue itself imposed by the data-link gradually attracted more attention than before. Coyn et al. (2005) demonstrated they will pay much attention to the influence of data age on the pilots’ use of METAR information. Attempt has been made to investigate maximum allowable delay on the display, no conclusive results have been obtained (Frank, Casali & Wierwille, 1988).

Novacek et al. (2001) had already suggested that delayed radar information could lead to noticeable error in estimating the proximity to severe weather area and in estimating the movement speed of storm cells. It is potentially because of the difficulty that pilots have when interpreting the age of information and the complex cognitive processes involved when subtracting the current time from the NEXRAD image timestamp and predicting the weather movement. So they suggested that a more intuitive timestamp design is necessary so that it can simplify the mental calculations to correctly determine the age of NEXRAD images. In this study, some participants stated that they were aware of the age of radar images. However, they considered 14 minutes old to be real-time, compared to preflight weather charts that could be over an hour old.

A similar problem was raised during experiments that tested data-linked weather information (Yuchnovicz et al., 2001; Latorella & Chamberlain, 2002). Many subject pilots in the studies commented that they perceived the NEXRAD weather image to be real time information, forgot the delays, or chose to ignore them because of their workload. When asked if they were aware of the age of the image, they generally commented that they were aware of the 7 to 14 minute delay at the beginning of the flight, but that they soon started to treat it as real time. Two pilots even commented that, to them, 7 to 14 minutes was real time compared to a pre-flight weather chart that could be hours old. When asked about how they used the timestamp information, most commented that they did not consistently determine the age of the NEXRAD image, but either ignored the delay or treated the image as delayed for a consistent amount and did not try to determine the age of the image. Most pilots incorrectly estimated the impact of the delay in determining the movement of the hazardous weather and their proximity to it. The conclusion indicated that delayed information contributed to the navigation decision error.

Yuchnovicz et al. (2001) suggested that the literature pertaining to data-linked weather information in the cockpit as it exists today is still in its infancy. The "infancy" has two kinds of meaning: not many studies and limited research angle. Most of the time, studies focused on situation awareness and decision making. For the reaction to the time-delay, most pilots chose to ignore it or treat it as real time. Some studies (Novacek, 2001; Yuchnovicz et al., 2001) suggested that weather systems display should provide the own-ship position, weather movement direction and rate, and intuitive NEXRAD image age. The timestamp used in the experiment (see Figure 3.2.) required that the mental calculations correctly determine the age of NEXRAD data. The concern with this timestamp lies in the interpretation difficulties and cognitive processes required in subtracting the current time from the NEXRAD image timestamp and predicting the weather movement.

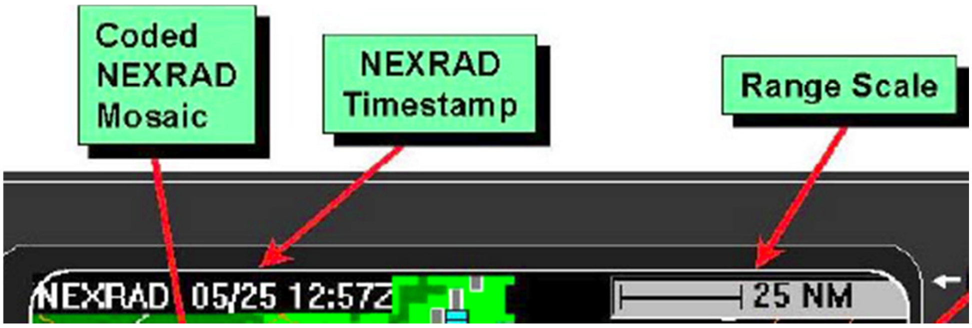


Figure 3.2 Timestamp of the project (Yuchnovicz et al., 2001)

The delayed NEXRAD information as are most of other products in the cockpit presented pilots with complex issues of recognition, interpretation of the age and prediction using the delayed information. Those studies (Novacek et al., 2001; Yuchnovicz et al., 2001; Latorella & Chamberlain, 2002) have indicated that pilots may not be fully aware or underappreciate the importance of the delay. In addition to the timestamp representation, the length of the delay represented by the timestamp and how pilots processed the delayed information is not yet clear. Yuchnovicz et al. (2001) proposed that less than seven-minute intervals of update frequency would have the most significant effect on the pilot's understanding of proximity to the hazardous weather. Whereas Latorella and Chamberlain (2002) implied that five-minute update rate is adequate for strategic use and more than a 10 minutes update rates is insufficient for appropriate use. In this study, one participant did recognize the danger inherent in using long-delayed information and mentioned that he compensated for this by looking only at weather very close to the aircraft symbol. However, this strategy was not successfully applied.

Kelly et al. (2000) raised several questions including (1) What NEXRAD update rate is necessary and how much latency is acceptable? (2) How can we indicate the age of the NEXRAD data? Few studies have offered exact answers. It is not clear, for example, whether pilots will try to extrapolate the current position of storm cells from delayed data and attempt to wave between areas of perceived danger (tactical use), or adopt a more conservative approach of longer-term route planning to avoid potential hazards altogether (strategic use). Burgess and Thomas (2004) also questioned whether the problems with accurately estimate storm cell movement is due to the difficulty of extrapolating the current position of storm cells and the age of the weather information or simply the limitation of pilot's cognitive process. So far, we only learned several points from those studies:

1. How to show the age of a NEXRAD image.
2. Delayed information is inaccurate and unreliable (Bustamanta, 2005). And the extent of NEXRAD's unreliability is partly dependent on the amount of time since its last update (Sherman, 2003).
3. If pilots could recognize and interpret the age of radar information with the support of timestamp, we are not sure whether pilots could use the delayed information to correctly determine the current location of storm cell, movement rate and proximity to the storm cells.
4. It is difficult for pilots to process delayed information and predict the trend.
5. What is the strategy of pilot that can mitigate the impact of age on decision-making, especially for the tactical decision?

To answer these questions, we need to know what tasks pilots perform when using time-delayed weather information during the flight. What kind of judgment pilots will make by using delayed weather information.

Chapter 4 Pilots Task Analysis

4.1 Task Analysis Methods

Task analysis is the basis for designing a human-machine interface (Sanders & McCormick, 1993), and overlaps both information display and information processing. That is, it bridges the gap between the display and users. Task analysis is a methodology that can be used to analyze and understand the tasks, goals, and information that is required to conduct the task and brought to the system (Spiller, 2003). The goal is defined as a user-defined and desired state of the system. The task is the compilation of the activities required to achieve a goal.

There are many task analysis methods such as Hierarchical Task Analysis (HTA), GOMS (Goal, operator, Method, Selection), and Cognitive Task Analysis (CTA). HTA is intended to show the structure of the work in terms of tasks, goals and actions. GOMS produces a description of a task, often in the form of a hierarchical plan similar to those produced by HTA. However, while HTA generally describes high-level activity, GOMS typically works at the keystroke level. CTA, which is knowledge-based as compared to behavior-focused HTA, concentrates on internal representations, language, knowledge structures and cognitive/perceptual filters. Focusing on users' cognitive processing and experiences, cognitive task analysis is typically used when tasks are complex or ill structured or when tasks occur in dynamic, uncertain and multi-tasking domains (Latorella et al., 2001). CTA has supported system design in military operation, aviation, air traffic control and driving (Prasanna &Yang, 2009).

Kirwan and Ainsworth (1992) introduced 25 major techniques of task analysis that were the most useful and representative in the process control field. The 25 techniques are grouped into five sections which define their major or most common roles.

1. Task data collection techniques are primarily used for collecting data on human-system interactions: activity sampling, critical incident technique, observation, questionnaires, structured interview, and verbal protocols.
2. Task description techniques structure the information collected into a systematic format to enhance the understanding of the human-system involvement: charting and network techniques, decomposition methods, HTA, link analysis, operational sequence diagrams, timeline analysis.
3. Task simulation methods involve creation of a dynamic model using: computer modelling and simulation, simulator/mock-ups, table-top analysis, walk through and talk-through.
4. Task behavior assessment methods are concerned with system performance evaluation from a safety perspective: event trees, barrier a work safety analysis, failure modes and effects analysis, faulty trees, hazard and operability analysis, influence diagrams.
5. Task requirement evaluation methods assess the adequacy of the facilities and the interface: ergonomics checklists, interface surveys.

Sometimes task analysis methods are not constrained within 25 methods. For the complex, high demanding and dynamic task, a comprehensive and tactical task analysis is needed. Farley et al. (1998) performed a comprehensive goal-directed task analysis for the commercial airline pilots. Compared to a traditional task analysis, CTA method is most appropriate in exploring much more complete and accurate picture of the domain and required information and decision. Goal Directed Cognitive Task Analysis (GDTA) is the typical method for the analysis of users' goals or cognitive demands (Prasanna &Yang, 2009).

Endsley (1993) conducted a GDTA to identify the information processing or situation awareness requirements of system users. The outcome of GDTA is a list of critical decisions and information requirements that can be used as a basis for display design, training program development and development of situation awareness assessment measures. However, in the context of aviation, the limitation of GDTA is that, the specific component actions required pilots to achieve a goal or sub-goals which are largely determined by the nature of the technology in the aircraft. It is possible that every significant change in the cockpit would require a separate task analysis (Beringer & Schvaneveldt, 2002). Actually the methods of performing of task analysis are difficult to understand and apply. And it is not clarified how to integrate complex human cognition and action with simple analysis techniques (Crystal & Ellington, 2004). Firstly the pilot's weather related tasks must be known, and then the task analysis approaches are carefully chosen.

4.2 Pilots tasks-- Proximity Estimation to the Storm

Understanding the information requirements of the tasks, cognitive and perceptual capabilities of the pilot, and the contingencies imposed by the task will help to ensure the safety of aircrafts (Ververs, 1998). Pilots use three cognitive dimensions to categorize flight-deck information (Jonsson & Ricks, 1995): the flight function, the strategic or tactical nature of information and the frequency of information referral. The information categories include: aviation, navigation, communication and system administration. Based on the information categories, Ververs (1998) categorized the modern commercial pilots' tasks into four general objectives: aviate, navigate, communicate, and manage systems. While navigating, the pilots need to be aware of the aircraft's position in relation to the desired trajectory and potential threats to the safety of the aircraft. Also, pilots use instruments to control and minimize the deviation from the intended flight path. Besco (1996) confirmed that good pilots could meet all the above requirements in addition to: detecting errors or failures, communicating their assessment of errors, staying mentally ahead of their aircrafts, and having confidence in the recurring errors.

Proximity estimation to the storm is very important for pilots in the operation of aircraft (Niall, et al., 1999). The pilots need to keep a safe relative distance between the aircraft and storm cell, that is, they pay much attention not only to the velocity of the weather, but also to that of the aircraft, since the relative rate between the weather and aircraft determines if and where the two may converge (Chamberlain & Lemos, 2004). The FAA Aeronautical Information Manual suggests that pilots avoid, by at least 20 nautical miles (40 km), thunderstorms characterized by "intense radar echo" for en route airspace (DeLaura et al., 2006). It is assumed that aircraft will seek to stay at least 10 NM away from any individual storm cell; otherwise it will not allow enough airspace for deviation.

Pilots may choose to keep away from the storm cells based on the weather conditions. Studies (Rhoda, 1999; Rhoda, et al., 2002) of pilot behavior suggested that pilots fly over high reflectivity cells in en route airspace and, penetrate lower cells whose reflectivity is less than 41dBZ. In the study of Delaura (2006), the definition of 'significant' weather was an echo top height greater than or equal to 25000ft. Weather conditions were divided into different levels based on the Vertically Integrated Liquid (VIL) level contours that may provide the best hazard boundary for deviation. Approximately 75% of all deviating aircrafts flew within 20 km of the level two VIL boundary, within 25 km of the VIL level three boundary and within 33 km of the VIL level four boundary. There is a lack of concrete evidence about what information sources are used by the pilot and which the deviation strategies may be imperfectly executed, therefore, the actual trajectory flown may not reflect the pilot's intent.

Without necessary information, own-ship, it is difficult for pilots to correctly determine their position in relation to the storm cells (Yachonovica et al., 2001). When determining proximity to hazardous weather on the weather information display, some pilots incorrectly estimated the distance from their location to the hazardous areas of the storm. The estimated distance is two to four times greater than the true distance. The misinterpretation of distance scale also impacts the misjudgment of proximity so it recommended that range ring and distance scale should be available on the radar image to aid in distance estimation.

The synthetic images of the real conditions on the display, generated by computer-animated, commonly contain systematic errors in size and distance judgments. For example, different levels of reflectivity of radar display affect the proximity of the aircraft to the storm cell (Beringer & Ball, 2003). Pilots with higher resolution NEXRAD imagery or no NEXRAD imagery tended to fly closer to the convective cells.

Chamberlain and Latorella (2001) investigated the effect of weather cue condition on the distance estimation. The results showed that the weather display + aural condition improved the likelihood of more accurate (25 NM) estimates marginally over the out-of-window +aural condition. The window + aural condition supported more accurate bearing estimates and were the most accurate for distance estimates.

Weather condition, resolution, and types of information display will affect the pilot's ability to estimate distance to the storm cell. Chamberlain and Lemos (2004) suggested that time looping to display data-linked radar information could graphically present the velocity of the aircraft and weather concurrently and reduce required cognitive resources by enabling the pilot to compare the closure rate and convergence location from the combined visual picture. Similarly, Bederson and Boltman (1998) found that animation helps users build up the mental maps of spatial information and reconstruct the information space. So the time looping might affect distance estimation.

4.3 Task Analysis for Delayed Radar Information Processing

In a word, during the navigation, the task of pilot must process the information from the map, navigational instruments and the instrumental panel to identify hazardous objects to be avoided (Wickens, et al., 2003). Based on the combined model of integration and SA (see Figure 2.3.), we know that delayed radar information processing of pilots has three sequential steps:

Step 1--displaying range ring, scale, timestamp, own-ship, and storm cells movement speed and direction: display integration --supporting level-one situation awareness

Step 2--internally compute the current location and distance between the storm cells and own-ship-- supporting level-two situation awareness (spatial awareness).

Step 3-based on the current condition between the storm cells and aircraft, pilots' project future distance between the storm cells and aircraft-- support level-three situation awareness and prepare for the pilots

Using task analysis method, the first step was analyzed into several goals that contain perceptual and cognitive elements. The pilots' task diagram is below (see Figure 4.1):

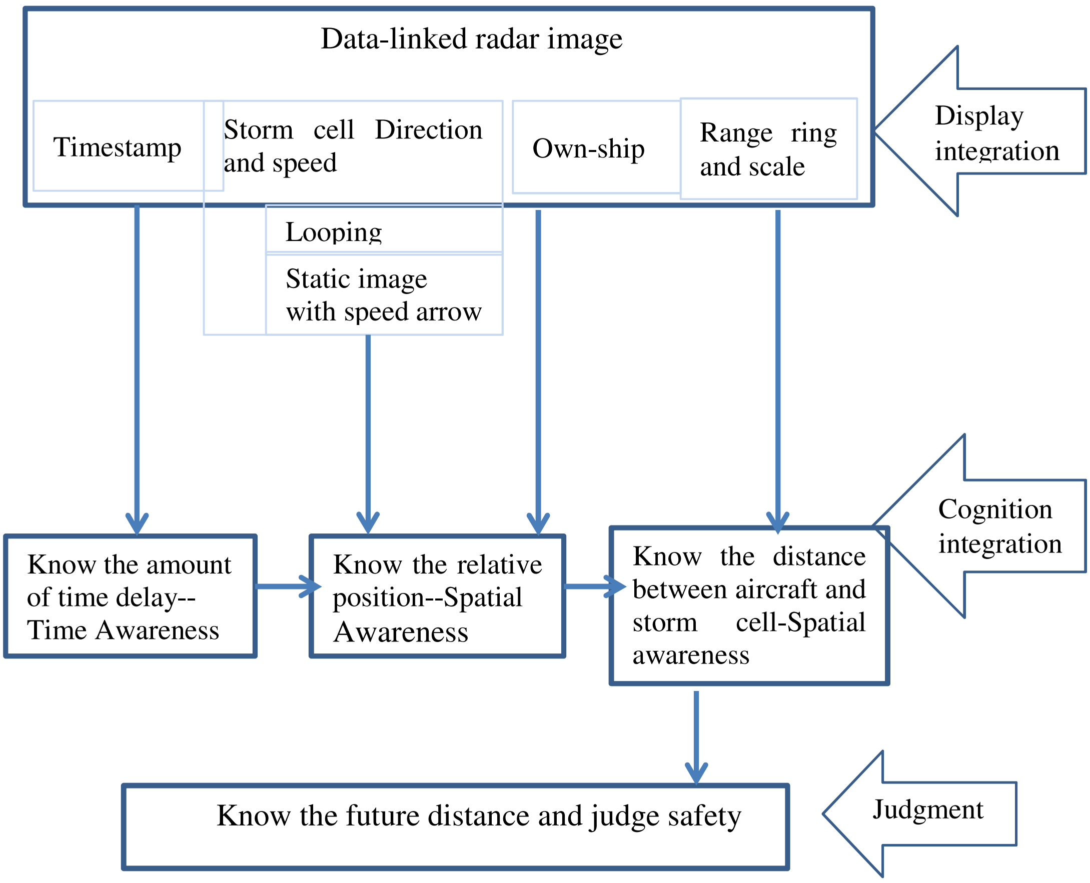


Figure 4.1 Task analysis diagram of pilot's processing of delayed weather information

With the data-linked radar image information, accurate analysis of data-linked information depends on your understanding of each feature on the radar image. In the task diagram, the first goal is to know the most intuitive way of timestamp representation so that pilots need no extra mental computation. The second goal is to know which display type, loop or static image with vector, is a good way to support spatial awareness. The third goal is to know whether the amount of time delay could affect the current location estimation and current distance estimation between the storm and aircraft. The fourth goal is to know whether pilots could estimate the future condition based on the delayed information. The extra goal is to test the three stages and spatial awareness component of SA by using objective and subjective methods.

Two experiments were designed to achieve these goals and test the effect of delayed radar information on the proximity judgment. The first experiment examines the use of representation for radar image's timestamp. The second experiment tests the effect of time delay on the pilots' distance estimation. The results will answer those questions the mentioned above.

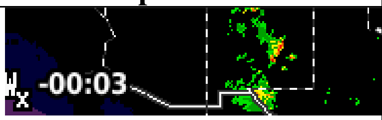
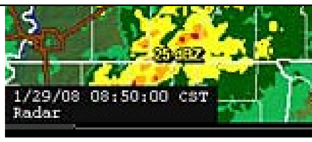
Chapter 5 Representation of Radar Image's Timestamp Experiment

5.1 Introduction

NTSB (2011) issued a safety alert to warn pilots that the NEXRAD "age indicator" can be misleading. Instead of the actual age of the NEXRAD data, the age indicator displays the age of the mosaic image created by the service provider. As a result, weather conditions depicted on the mosaic image will always be older than the age indicated on the display. The difference between the actual time and age indicator may have played a factor in the deaths of at least two pilots.

Age indicator or timestamp has been represented in several ways (see Table 5.1). In Garmin XM weather system, the timestamp consists of a minus symbol and the time. The minus symbol apparently shows the elapsed time, which makes it easy for users to know the age of the radar information. In WSI, The data freshness indicators on each button use color codes to show the currency of the last-received weather products by changing the appearance of the corresponding product's button. Users need to learn broadcast cycles of weather features. In WxWorx, the timestamp in the map window will display the date and time that the data is issued or available. Users need to compute by themselves how long the time elapsed or the age of the weather information. For the XM WX data products (http://www.xmwxweather.com/xmwx-data/data-products.html), the timestamp is in a standard format: "hour: minute: second". Coordinated Universal Time (UTC) is the time standard used in aviation, such as for flight plans and air traffic control clearances. Weather forecasts and maps all use UTC to avoid confusion about time zones.

Table 5.1 Types of timestamp

Weather Systems	Timestamp	Format
Garmin XM		"-hour: minute"
WSI		"hour: minute"
WxWorx		"hour: minute"
XM WX		"hour: minute: second"

Few studies have examined the appropriateness of the timestamp standard itself for aviation-relevant decisions. Moreover, it is difficult to determine if the timestamp standard is consistent across different organizations that produce radar mosaics. Many pilot decisions are near-tactical and require a timestamp that properly characterizes the time/age and affords the ability to properly process the age of the radar mosaic image. The objective of this experiment is to find intuitive timestamps to help pilots process and take the time delay into account. Intuitive representation of timestamp would reduce the extra mental processes, improve the time delay perception of pilots, and enhance time awareness.

5.2 Timestamp Representation

Weather information should be presented in an optimal form that makes it quickly and unambiguously useful as an aid for decision making (Lindholm, 1997).

Human factors scientists recommended that more intuitive timestamps were needed to alleviate the mental demand necessary to correctly determining the age of NEXRAD images (Burgess & Thomas, 2004; Latorella & Chamberlain, 2002; Yuchnovicz et al., 2001; Novacek et al., 2001). In this study, different age display formats will be systematically compared. SAE (1990) denotes that the data-link message content/phraseology/ symbology shall be designed to prevent misinterpretation and ease interpretation of the message. For example, the timestamp on the display clearly indicates the time of the composed weather report but not the observation time. The way for displaying the timestamp will affect how pilots process the delayed weather information.

In summary, timestamps of these weather systems have two formats. Standard UTC format denoted the information issued time as: "hour: minute: second", or alternatively the amount of time delay could be shown directly as: "- hour: minutes". Another possible representation of time could be through an analog clock display, which shows current time and displays time with two hands, and highlights the area between the two hands to represent the amount of delay. So far, few studies have investigated the most effective way to display the time delay for the weather information.

Unlike the analog representation, the digital representation can be set very precisely and operates on a 24 hour cycle. Brunswik's (1956) demonstrated a lack of precision in judgments based on graphic representation, although graphical information often is found to be superior to digital information. Hansen (1995) examined several studies, some of which compared digital and graphical representation. The graphical representation led to large numbers of responses close to the right answers and low variability, whereas the digital representation gave more precise, correct answers but with a much higher standard deviation. In a comparison of mental subtractions on analog and digital watch displays, van Nes (1972) found that in order to determine a relatively small time difference quickly and precisely from the displays, the representation should be digital. If only a rough estimation (e.g., a full or half hour) is needed, subtraction is believed to be easier with an analog representation. According to Van Nes (1972), the ideal time display would provide both representations, and in fact this is now available on several types.

Compared with analog representation, digital display could be more precise, compact and economical (Miller & Penningroth, 1997). So many displays that in the past would have been in analog format are now being designed with digital readouts. However, digital displays are not always superior to analog displays (Sander & McCormick, 1993), particularly when the task requires spatial processing or has rapidly changing display values. Miller and Penningroth (1997) stated that many previous studies have been designed primarily to test theoretical rather than applied questions. Although the tasks in these studies have resembled those that real-world users might have to do, such as telling time and matching one display with another, those tasks only tested more theoretical predictions than for their external validity. Under some conditions, the digital display might be more effective than the analog display. Rather, the designer needs to know under what circumstances one is superior to the other, and by how much.

Besides the difference between the digital and analog representation of time, we also need to notice the format difference among different digital representations. The general format is UTC or “hour: minute”. If we need to know the age of radar information, we need to first check the current time from a watch or clock and then get the age by mentally subtracting the time shown on the radar images. Latorella and Chamberlain (2002) reported that half of the participants didn’t use the age formatted in “hours: minutes” for the decision even though they on average agreed that the age representation is fairly apparent. The format,”-minutes”, directly shows the amount of time delay and requires no additional mental computation.

Another dimension of the problem is the amount of delay that needs to be displayed. Depending on the amount of delay, the mental processes required to gauge the delay might differ among the three timestamps. Thus, in the present study the three proposed timestamp formats were assessed under three different delays including: short, medium, and long delays. The goals of the experiment were to determine how best to support fast and accurate judgments by users considering the time delay of radar images. Our hypothesis is that “direct age” timestamp is the best way to represent the amount of time delay for radar images.

5.3 Method

5.3.1 Participants

Participants were recruited from the University of Oklahoma-Norman campus (OU-NC IRB No.0977) with a mean age of participants was 22.6 years (SD = 2.24). Nine men and twelve women comprised a total of 21 participants that took part in this experiment. All of which had normal or normal-corrected vision with no color blindness. Four participants reported that they learned radar images from TV and websites. All participants gave informed consent and some were reimbursed with course credits.

5.3.2 Materials

Stimuli were displayed on a 20-in LCD monitor with a resolution of 1600 × 900 pixels. Stimuli included a set of 745 × 568 pixels screenshots of radar images captured from Weather Scope 1.9.3 software that was developed by the Oklahoma Climatological Survey. Adobe Photoshop CS2 was used to generate the timestamp on the radar images. The position of the timestamp was 0.7cm from the bottom and 2.6cm from left side of the radar images. Three types of timestamps were named as direct age, clock, and UTC (see Figure 5.1, Figure 5.2, and Figure 5.3).

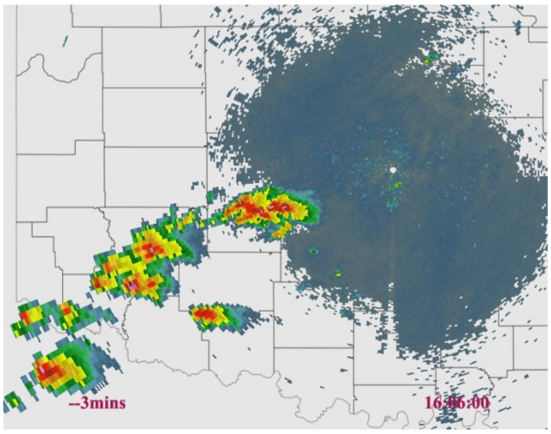


Figure 5.1 "Direct age" timestamp.

The amount of time delay indicated by the timestamp on the left side of the images was three minutes old. The time on the right of the images denoted the current time. Participants tasks involved comparing "-3mins" with, for example, "-5mins" and determining the “-3mins” timestamp was more recent. Participants could ignore the current time.

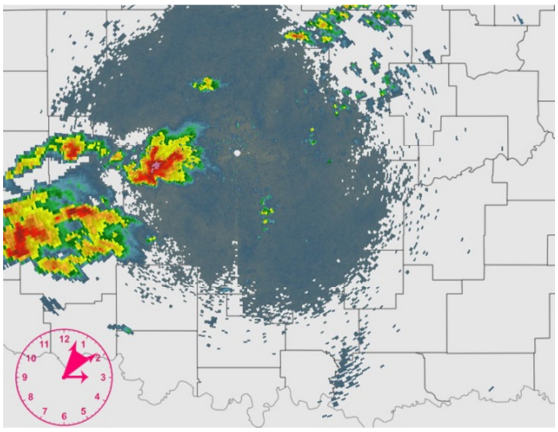


Figure 5.2 “Clock” timestamp

In the “clock” timestamp format, both observation time and current time were shown on the analog clock face. The two longer hands pointed to the “minute” and the one shorter hand pointed to the “hour”. The upper long hand pointed to the minutes when the radar observation was made and the lower long hand pointed to the current minutes. The red area between the two long hands indicated the amount of delay. During the task, participants would only compare the size of two red areas with a smaller area indicating the radar image was more recent

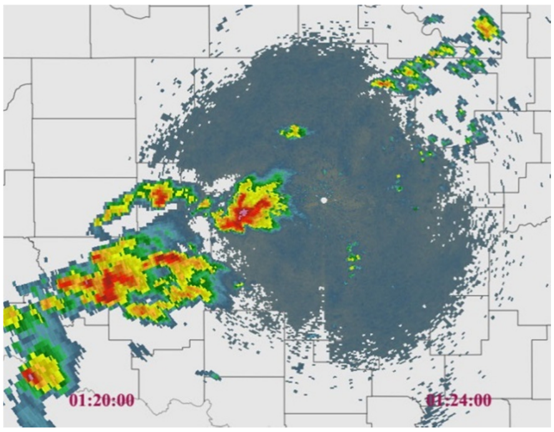


Figure 5.3 “UTC” timestamp

In the “UTC” timestamp format, both observation time and current time were presented in UTC format on the image. As shown in the figure (see Figure 4.1(c)), the timestamp on the left side showed observation time and the timestamp on the right side was the current time. The amount of delay can be derived by subtracting the observation time from the current time, which represented a four-minute delay in this example. Compared with the other side of the image with seven-minutes delay, image with four minutes delay seemed to be more recent.

The independent variables included (see Table 5.2.): types of timestamp (UTC, direct age, clock) and the amount of delay (short (1-9 min.), medium (10-19 min.), long (20- 29mins). Both independent variables were within-subject. The dependent variables included: accuracy of task and response time. Accuracy was calculated by dividing the number of correct answers by the number of trials for each combination of conditions, which are 15.

Table 5.2 The 3x3 Experimental Designs

Type of timestamp / **Amount of delay**	**UTC**	**Age**	**Clock**
Short (1-9 min)	15	15	15
Medium (10-19 min)	15	15	15
Long (20-29 min)	15	15	15

The hypothesis is as follows:

- “Direct age” timestamp will have the shortest RTs and highest accuracy
- Longer time delays will lead to less accurate and longer RTs
- Timestamp format and delay will interact significantly

5.3.3 Procedure

Before the experiment, participants needed to sign the consent form and fill out the demographic questionnaire. Next, the participants learned the definition of timestamp, as well as the types of timestamps and the amount of delay with a set of PowerPoint slides. The experiment interface was programed using Matlab2008b to simultaneously show a pair of radar images with the same timestamp format. The participant's task was to judge which one of the two radar images was more recent based on the timestamp. If participants chose the radar image on the left side, they clicked "more recent" button on the left side and vice versa (see Figure 5.4). The images were displayed for 10 seconds and the display order was random. With 45 trials for each type of timestamp, the whole procedure took about 20 minutes.

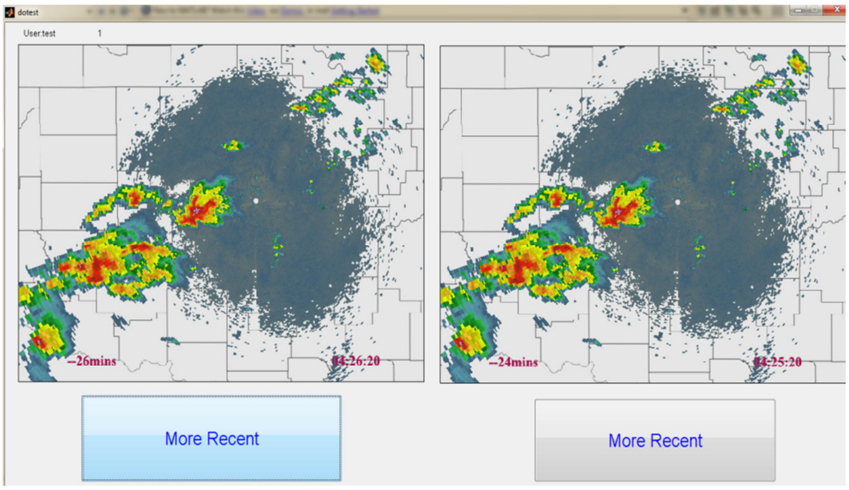


Figure 5.4 The interface of the experiment

5.4 Results

5.4.1 Types of Timestamp Effect

Different timestamp designs entailed different cognitive processing of the participants. The "age" timestamp directly showed the amount of delay so the participants' task was simply to compare the two numbers in the pair of radar images. For the "clock" timestamp, participants needed to compare the size of two areas formed by the minute-hand on the clock face. For the "UTC" timestamp, participants needed to subtract current time from issued time and then compared the two results. Obviously, "UTC" timestamp required more mental computation than the other two types of timestamp.

A repeated measure of SPSS 16.0 GLM was performed to compare means among three types of timestamps and three levels of time delay on the percentage correct and response time. Results for the "direct age", "clock" and "UTC" at three levels of amount of time delay were displayed in table 5.3. The percentage correct was significantly different among three types of timestamp ($F(2, 19) = 11.404$, $p < 0.001$). Post Hoc test revealed that the percentage correct of direct age ($M = 93.44$, $SD = 2.363$) was much higher than the clock ($M = 74.6$, $SD = 4.033$) and UTC ($M=74.28$, $SD = 3.711$) (see Figure 5.5).

Table 5.3 Percentage correct (%) mean (Sd.) of three types of timestamp

	Direct age	**clock**	**UTC**
Short	96.12 (9.1)	84.13(28.2)	79.36(18.7)
Medium	93.65(11.1)	80.63(19.9)	68.57(19.9)
Long	9.48(15.4)	59.05(17.9)	74.92(20.5)

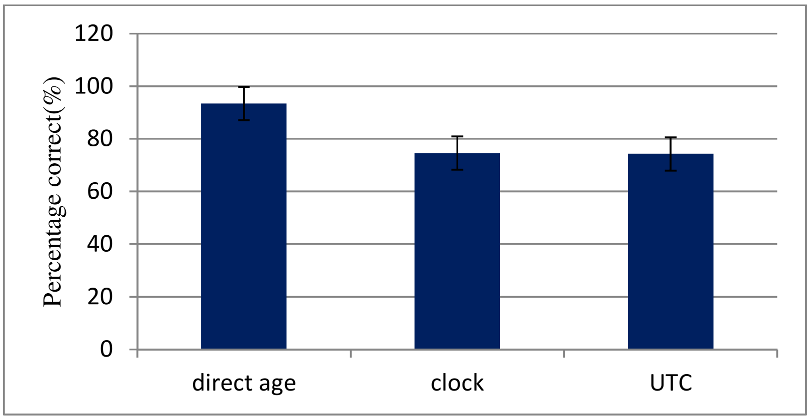


Figure 5.5 Percentage correct of timestamps

For the response time, there was a significant difference among the three types of timestamps ($p < 0.001$, $F(2, 19) = 34.89$). The response time is shown in the Figure 5.6. Post Hoc test revealed that the response time of direct age ($M = 2.03$ sec, $SD = 0.137$) is much less than the clock ($M = 2.644$ sec, $SD = 0.139$) and UTC ($M = 3.38$ sec, $SD = 0.146$).

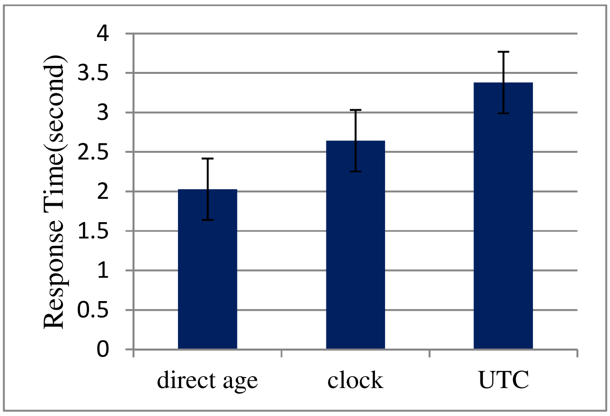


Figure 5.6 Response time of timestamps

5.4.2 Amount of Time Delay Effect

The amount of time delay affected the judgment of the time delay. The percentage correct was significantly different among three levels of amount of time delay ($p < 0.001$, $F(2, 19) = 16.597$). The average percentage correct of timestamp that was correctly selected by the participant was shown in the Figure 5.7 for the three levels of time delay. The Post Hoc test revealed that the percentage correct of short delay (M = 86.56, SD = 2.446) is much higher than the medium delay (M=80.95, SD = 2.298) and long delay (M = 74.81, SD = 2.72). The short time delay (ranged from 1 to 10 minutes) was expressed with a digital number or small pie area, which required a simple mental computation by the participants. In the comparison task, it was easy for participants to compare small numbers or small area within the shortest response time and achieve a highest percentage correct.

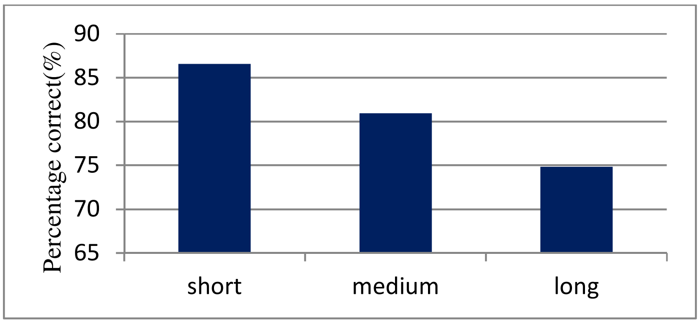


Figure 5.7 The percentage correct of three levels of time delay

For the response time, there was also significant difference among three levels of time delay ($F(2, 19) = 85.254$, $p < 0.001$). The response time was much shorter during short time delay (M = 2.427, SD = 0.098) than the medium time delay (M = 2.751 sec, SD = 0.106) and the long time delay (M = 2.874 sec, SD = 0.116) (see Figure 5.8).

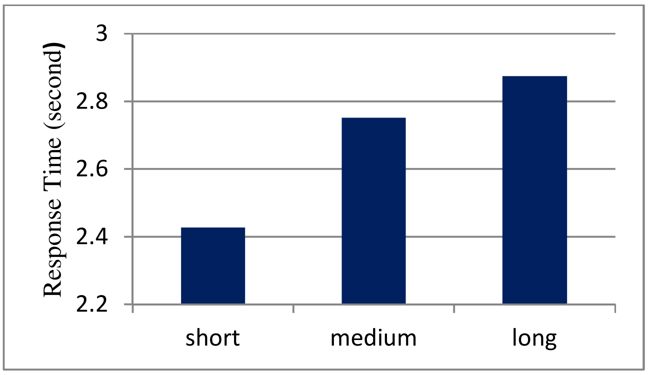


Figure 5.8 The response time of three levels of time delay

5.4.3 Interaction Effect

In addition to the significant main effects, a significant interaction effect was found ($F(4, 80) = 9.63$, $p < 0.001$) for percentage correct between timestamp types and amount of time delay (see Figure 5.9). For the "clock" timestamp, the percentage correct associated with long time delay was much worse than the other two types of timestamp. It was difficult for participants to compare larger area on the clock face in the analog format of time display. For the "age" timestamp, there was no big difference among three levels of time delay, because it was easy for participants to perceive the time delay. For the" UTC" timestamp, medium time delay seemed to be more difficult to process than the other two types of timestamp.

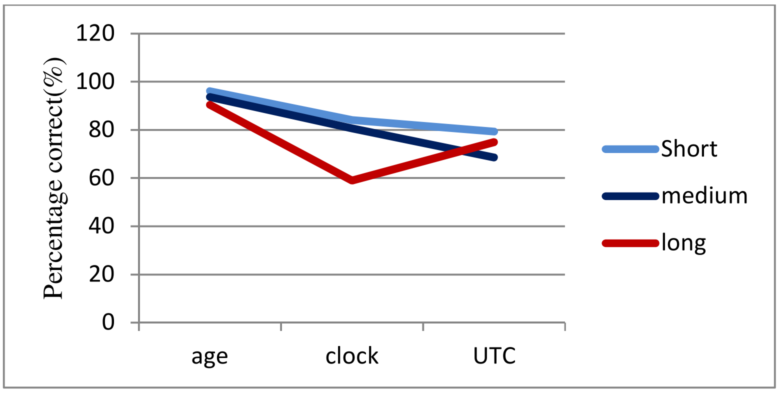


Figure 5.9 The interaction between the types of timestamp and time delay

A significant interaction effect was also found for the response time ($p = 0.004$) (see Figure 5.10.). For the "UTC" time stamp, the medium and long time delay had very similar response times. This might be because both medium (11-20 minutes) and long delay (21-30 minute) involved delay of two digit numbers, whereas short delay only involved calculation with one digit numbers (1-10 minutes). It was easier for participants to carry out mental subtraction for problems that resulted in a one digit difference rather than a two digits difference.

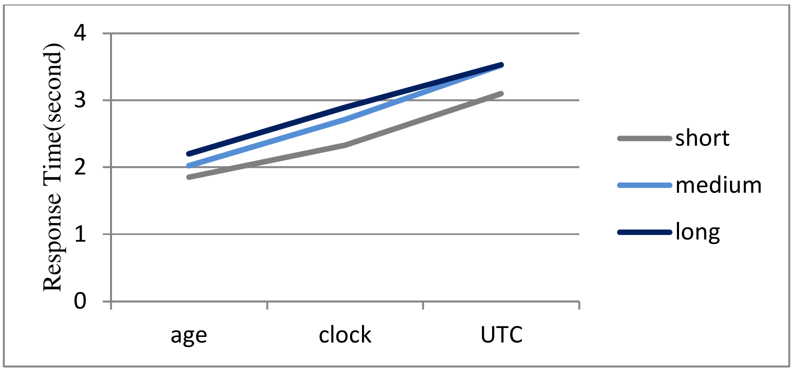


Figure 5.10 The interaction of response time

In summary, medium or long time delay made it more difficult to perform mental subtraction than a shorter time delay, which resulted in lower percent correct and longer task time. For the "clock" timestamp, the red area represented the amount of time delay. Participants had difficulty in comparing long time delays for the "clock" timestamps because relative differences between large areas were indistinguishable. When the size of area was small, it was easy for participants to compare; however, it was not precise since there was no big difference between long and medium time delay. In a word, the "direct age" timestamp was the best way to represent the amount of time delay among three types of timestamp because the participants had the fastest response time and high accuracy.

5.4.4 Discussion

It was expected that "direct age" timestamp would be the best way to represent time delay. The results of the experiment confirmed this expectation since "direct age" timestamp led to the highest accuracy and fastest response time. For the "direct age" timestamp, the task is to compare two numbers. Long time delay meant bigger numbers and led to slower response time and lower percentage correct than short time delay. For the "clock" timestamp, long time delay meant the pie area is large. It is difficult for participants to compare two pieces of large pie area. Since the format of the "UTC" timestamp was "hour: minute: second", generally, the "UTC" timestamp was represented with more numerals than the "direct age" timestamp, and participants required more time to process the images. Furthermore, participants also needed to take time to mentally subtract the observed time from the current time. So in the limited display time, the "UTC" timestamp was less effective for representing the time delay.

Since the comparison task needed no specific weather knowledge and flight experience, students were recruited as participants. According to the time comparison task in this experiment, we could conclude that the "direct age" timestamp is the best. However, pilots might need to perform other tasks related to the display time, and we did not investigate all possible tasks in this study. According to Wickens et al. (1983), compatibility between the stimulus, the cognitive processing and the response is required for the task (S-C-R compatibility). If the information displayed matches or corresponds to the type of processing and response required for the task, then the task will be performed more quickly and effectively than if no such compatibility exists.

In the three timestamp formats that we studied, the UTC format is the most commonly used timestamp in weather websites and weather systems. Through the empirical investigation, it was shown that the "direct age" format was more effective in conveying the amount of delay. The analog clock display was not better than the UTC standard format in conveying the long time delay. These results can be used to enhance pilots' time awareness in time sensitive conditions.

Chapter 6 Effect of Delayed Radar Information on Judgment

6.1 Introduction

By convention, radar mosaic products are stamped with the time of the last (i.e., youngest) piece of radar data used to create the mosaic image. In the first experiment, the type of timestamp was investigated for effectiveness in representing the amount of time delay. In this chapter, the results of the “direct age” timestamp on the radar image were used. The goal is to investigate the effect of amount of time delay on the pilots’ judgment. In this chapter, “amount of time delay” and “age” are two interchangeable terms.

Previous studies (Yuchnovicz etc., 2001; Latorella & Chamberlain, 2002; Novacek, 2001; Burgess & Thomas, 2004) indicated that pilots ignore, underappreciate, and misinterpret time delay. This is partly because the methods for the representation of timestamp make it difficult to recognize age, needed extra mental resources to interpret, and was easy to misunderstand. Without an intuitive timestamp, own-ship, and scale, pilots overestimate the proximity to hazardous weather areas and inappropriately interpret radar information, which may have serious consequences.

The “direct age” timestamp was shown to fully support the time awareness and effective for representing time delay. Thus, pilots will not have the intent to ignore and misinterpret delay issues or treat images as real time. According to the study of Latorella and Chamberlain (2002), providing the own-ship, scale of distance and bearing, intuitive timestamp, and looping or static with movement vector, could pilots make accurate proximity estimation to the storm using delayed radar information appropriately? Based on the model of information integration and SA, it is not easy for the pilots to make a simple judgment regarding their position relative to a convective cell and the inherent risk. Therefore, the amount of time delay and weather condition (movement speed and development rate) must be considered.

The model (see chapter 2 Figure 2.3) and task analysis diagram (chapter 4, Figure 4.1) illustrated three issues concerning the delayed radar information in addition to the timestamp representation. Viewing delayed radar information, situation awareness is a time sequence, representing past, current, and future, although the time interval may be just at most 20minutes old. So the first issue is whether the display supports current estimation and how well pilots can use old information to forecast the current condition. Although looping of radar image provides the movement, speed, and direction, pilots may not be certain of their estimates for the distance of storm movement. Burgess and Thomas (2004) mentioned that pilots would use the delayed radar information for prediction, but it was not clear whether pilots could use delayed weather information to extrapolate the current position of a storm cell. Secondly, it is unknown whether pilots could make accurate current distance estimations to storms using delayed information. Thirdly, it is still unknown whether pilots could make accurate future distance estimations and have good spatial awareness.

Since data-linked radar images enable pilots to view weather conditions at a larger scale than on-board weather radar and afford strategic planning with regard to the weather (Lankford, 2002), pilots will continue using data-linked radar information. However, it is useful to investigate the issues pertaining to the delayed radar information for enhancing pilots' time awareness and spatial awareness.

6.2 Type of Storm Movement Display

Doppler weather radar is a type of radar used to locate precipitation, calculate its motion, and estimate its type (e.g., rain, snow, and hail). It also can be analyzed to determine the structure of storms and their potential to cause severe weather. Radar sends directional pulses of microwave radiation and each pulse bounces back to the radar when detecting those small particles. Return echoes from targets (reflectivity) are analyzed for their intensities to establish the precipitation rate. On the radar images, radar returns are usually described by colors that normally range from blue to red for weak returns and strong returns. Based on the U.S. National Doppler Radar site, number scales used to represent different levels of reflectivity indicating amount of rainfall: magenta--65dBZ (heavy precipitation), red--52dBZ, yellow--36dBZ, green--20dBZ (light precipitation). In the study of Burgess and Thomas (2004), a "keep out of red" heuristic may be adopted by pilots to avoid the hazardous weather area.

Pilots reportedly avoided hazardous weather and determined the movement of convective weather by using looping or vector arrows (Novacek, 2001). Burgess and Thomas (2004) compared two types of display that provide the storm movement information: looping NEXRAD and National Convective Weather Forecast (NCWF) product. The goa of this studyl tried to investigate the decision making in IFR flight when using the two displays. The results showed that two displays increased the situation awareness with respect to location, proximity, and movement direction. However, there is no significant difference between the two displays regarding to the understanding of latency, quality of decision, mental workload, and situation awareness.

It was suggested that storm movement vector, storm speed, and range ring were very helpful in dealing with the complex decision.

Chamberlain and Lemos (2004) demonstrated that static weather radar image depicts the spatial nature of complex weather situations, but provides no direct cues about temporal changes, or weather trends. Weather looping graphically depicts a storm system's recent velocity and growth or decay by presenting a sequence of historical images, which resulted in a more complete mental map of the spatial information. Further, animation may be considerably more effective than static graphics for weather convergence and re-routing. From this animation, pilots can extrapolate what the weather will likely be in the near future. Looping is the preferable option, but limited objective performance data are available regarding the effectiveness.

On a NEXRAD radar image, the arrow is used to show the forecast movement of storm cells. The arrow length indicates where the cells are forecasted to be in 60 minutes. The speed denoted by the arrow provides quantitative information while the animation provides qualitative information (Ware & Plumlee, 2013). Quantitative information should provide clear and precise scales, scale units and scale marks; qualitative information could use color and shape to represent the range of values (Sanders & McCormick (1993). Extra mental computation is required to process and understand the quantitative information, but it is uncertain if display features, such as vector arrow help to make more accurate distance estimation than animation?

An ideal weather looping presentation would provide pilots with a high level of weather trending awareness but require minimal time expenditure, cognitive resources, minimal data-link capacity, and avionic performance. There are many looping design options to consider in pursuit of this ideal, including: image resolution, elapsed time, a number of frames, and cycle time of the loop. The study of Chamberlain and Lemos (2004) showed that a minimum of five frames with at least 1.0 second loop time had benefited performance measure.

6.3 Amount of time delay

Different weather systems have different update rates and ages for radar images. The XM GARMIN, for example, updates NEXRAD radar information on five minutes cycles. For the GARMIN G1000, the expiration time of NEXRAD is 30 mins. For the WSI NOWrad, the update rate is five minutes. The data available to the pilot via the data-link could be as old as 14 mins (Burgess & Thomas, 2004). According to NTSB (2011), the age of radar image is about 20 minutes old. The question is whether the amount of update or time delay affects the judgment. Even at the 10-min scale, rapid vertical development of cell (>3000ft/min) can make the difference between over-flight and lateral avoidance (Arend, 2003). Few studies were concerned with the effect of the amount of time delay.

6.4 Storm Cell Movement Speed

Pilots need to be able to recognize hazardous thunderstorm patterns depending on the type and movement of precipitation (Lankford, 2002). These patterns include greater than 20000ft storm top, rapid echoes movement, and rapidly growing storm. Severe weather often accompanies a single thunderstorm, or a line or cluster of echoes moving at 40 knots or more. Stronger radar returns normally indicate a higher probability and severity of turbulence and hail, which can extend above, below, and to 20NM away from the storm. Rapidly growing storms can increase in intensity in minutes and grow at the rate of 7000ft/min.

Based on the summary of Edwards (2011), thunderstorms generally last 30-60 minutes, but sometimes they can last for over eight hours. Thunderstorms have three distinct stages: developing stage, mature stage, and dissipation stage; three levels: strong /severe storm, mid-level storm, and low-level storm. There are five types of storms on radar based on the physical characteristic: single cell storm, pulse storm, multicellular cluster, multicellular line, and super-cell. The NWS defines a severe thunderstorm as having large hail and damaging winds of at least 50 knots.

The average tornado moves at a speed of about 23-25 knots, but some others have traveled faster than 48 knots. 82 percent of the storms move within plus or minus 10 knots of the mean speed of 32 knots. Shearman (1977) confirmed that most storm movement speed is greater than 32 NM. Thunderstorms typically move at speeds of 3-54knots. Modern radars take from 3 to 6 min to scan a volume. A fast storm travelling at 54 knots will move from 3-5 NM during that time. Storms typically have diameters of 1-11 NM. For storms which are separate and distinct, the lateral spacing between an adjacent pair will be at least as great as the mean diameter for the pair. So the spatial separation between an adjacent storm pair is somewhat greater than their mean diameter and may be as low as one nautical mile, though this is rare and usually the separation exceeds 3 nautical miles. There is clearly a chance of ambiguity in the match from one scan to the next because the storm separation is sometimes less than the distance moved between scans.

6.5 Task Analysis and Objectives

When flying in an area that is subject to severe weather, Burgess and Thomas (2004) demonstrated pilots must make a number of judgments and decisions. First, pilots need to determine if the weather is hazardous. Second, pilots must determine the proximity of aircraft to the hazardous weather. Third, pilots must determine if the hazardous weather is going to impact their flight path, and pilots must decide whether to divert to avoid the hazardous weather or continue to fly. If the weather information is delayed a couple of minutes, pilots need to make additional judgments. First, pilots need to know the time delay associated with the weather information. Second, pilots need to estimate the current location of the weather area and current proximity to the aircraft. If the weather condition is complex and not close to the aircraft, pilots need to predict future weather conditions so they can avoid the hazard

Based on the model and previous studies, objectives included:

1. Does the quantitative information provided by the vector arrow help to make more accurate distance estimations than animation? Could pilots estimate the movement, speed, and current location based on the animation display?
2. Whether the amount of time delay could affect the current location estimation and current distance estimation between the storm and aircraft.
3. Whether pilots could estimate the future condition based on delayed information.
4. To test the three stages and spatial awareness component of SA by using objective and subjective methods.
5. To understand pilots' strategy in handling time delay information.

6. To understand how much delay is acceptable.

Independent variables included levels of delay, types of moving track representation (animation, static image with speed arrow), and storm cell speed (fast, medium, slow). The main dependent variable was the closest approach distance. The closest approach distance (nautical miles) (Beringer & Ball, 2003) to the storm cells (red area) was measured by calculating the distance from each own-ship to the closest edge of the red area. This value was then used to calculate the difference between the actual approach distance and estimated approach distance. Other dependent variables include response time (how long participants process information), hazard level judgment, and certainty judgment.

Weather scenarios will be arranged according to the independent variables. That is, scenario types can be characterized by the aircraft's distance and speed of approach to various weather patterns with different moving speed and direction. The original distance between the aircraft and storm cell was chosen randomly. According to Mohee and Miller (2010), the average moving speed of thunderstorm was about 36.68mph or 31.87 knots. In this study, three types of weather scenarios were assumed including: storm cells movement speed is about 20-35knots, 35-50knots, and greater than 50knots. The storm cells have duration of 30--180mins.

The relationship among variables is described as follows (see Figure 6.1):

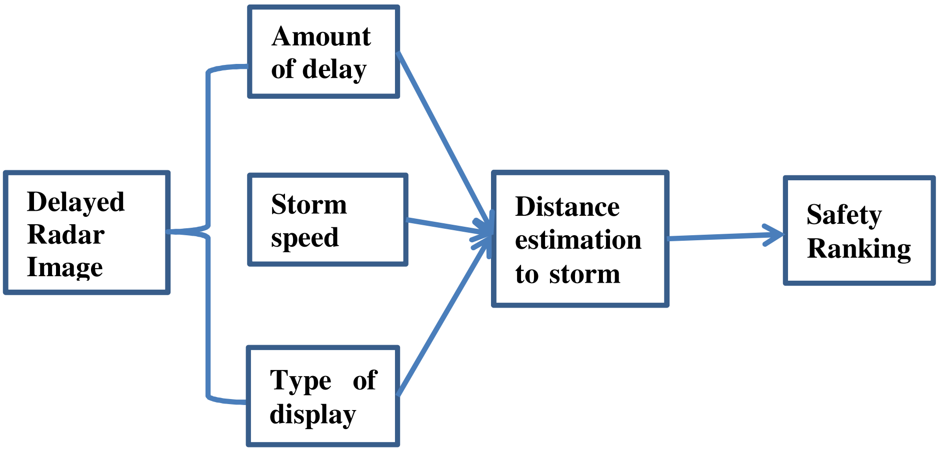


Figure 6.1 Independent variables and dependent variables relationship.

The hypothesis will be as follows:

1) Use of static image to estimate distance and location results in greater accuracy than animation
2) Distance estimation is more accurate during slow movement than during fast movement.
3) Distance estimation on short time delay is more accurate than on long time delay
4) Fast moving storms and long-time delay will require a longer response time than slow movement and short time delay

6.6 Methodology

6.6.1 Participants

A total of 31 OU student pilots and pilots were recruited from the aviation department of University of Oklahoma-Norman campus (OU-NC IRB No.0977) to participate in this study. The average age of participants was 27.8 (SD =10.81, Max =

55 yr., Min = 20 yr.). All participants had normal or normal-corrected vision. About half of the participants had instrument rating. Based on the demographic survey, ten out of 31 had logged more than 1000 flight hours, eight out of 31 had logged 300 -500 flight hours, and 12 out of 31 had less than 300 flight hours. Ten out of 31 participants had poor weather knowledge. Using non-parametric correlations, there is significant correlation (Spearman $\rho \leq 0.000$) between flight hours and weather knowledge. Based on the relation, pilots with higher flight hours had better weather knowledge.

6.6.2 Materials

Stimuli were displayed on a 20" LCD monitor with a resolution of 1600 × 900 pixels. Stimuli consisted of a set of radar images captured from Weather Scope 1.9.3 software that was developed by the Oklahoma Climatological Survey. Stimuli were either: animations (see Figure 6.2 (a) (b)); static images (see Figure 6.2 (c)). The frames of animation and static images were screenshots with 1023 × 755 pixels captured using Photoshop CS2. Adobe Photoshop CS2 also was also used to generate the timestamp, range ring and arrows for the static images.

There were ten frames in one animation and the display time for each frame was 0.5 sec. The time interval between two frames was 5 min. On the last frame, there was range ring, timestamp and geographic scale. The nose of the aircraft was at the center of the ring. Using animation, pilots could learn the direction and speed of movement. On the static image, the arrows directly indicate the direction and speed of movement. The range ring around the aircraft represented 40 NM of radius. The marked point, X, is the location where the storm was located at the time of timestamp so participants need to estimate the current location of the marked point.

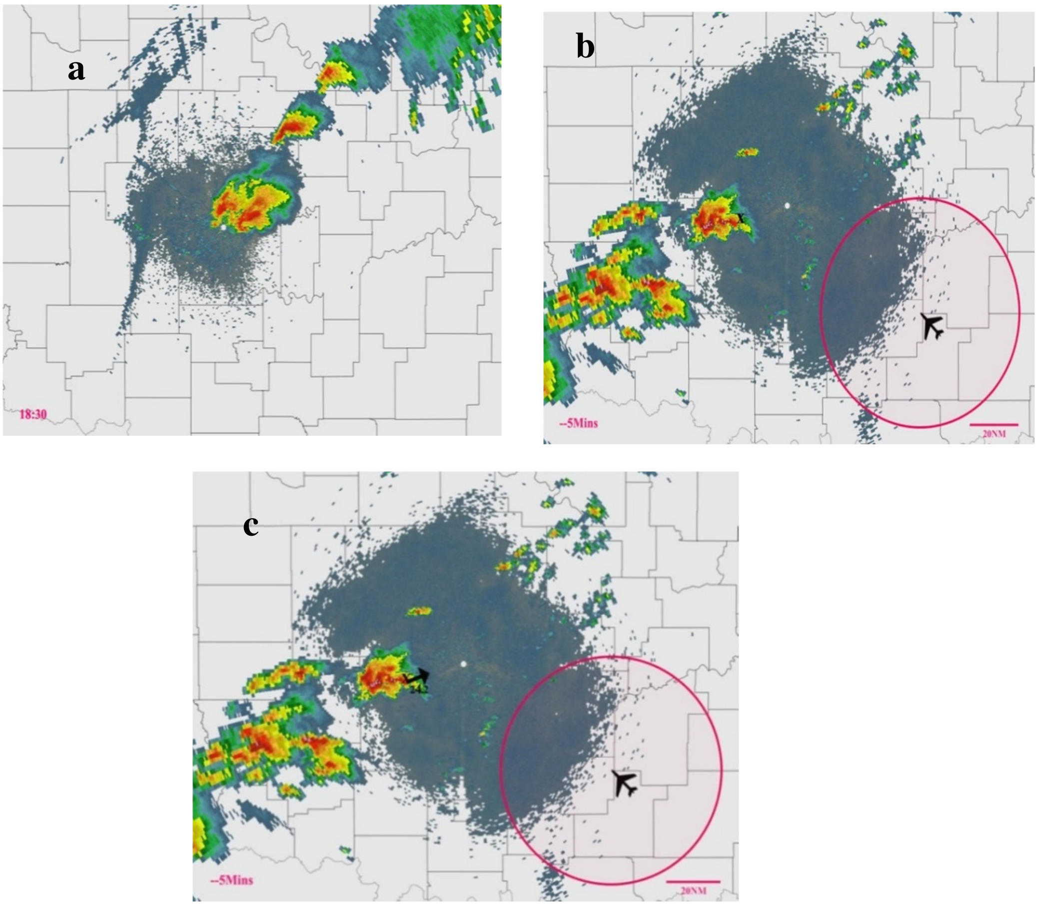


Figure 6.2 (a) A selected frame of animation; (b) The Last frame of animation; (c) Static image

This experiment is within-subject design with three factors, 2 (type of display) × 3 (movement speed) × 3 (amount of delay). Each factor levels combination had three trials. The trials were the weather scenarios chosen from the database of NOAA Storm Prediction Center. There were a total of 54 trials for the participants. For the short time delay, the fastest storm could move 4-5NM. For the medium time delay, the fastest storm could move 8-10NM. For the longest time delay, the fastest storm would move 20 NM (see Table 6.1.).

Table 6.1 The distance range storm moving under certain time delay and speed

	Short-5mins	**Medium-10mins**	**Long-20mins**
Slow(20-35knots)	2-3nm (3 trials)	4-6nm (3 trials)	8-12nm (3 trials)
Medium(35-50knots)	3-4nm (3 trials)	6-8nm (3 trials)	12-16nm(3 trials)
Fast(50---knots)	4-5nm (3 trials)	8-10nm (3 trials)	16-20nm(3 trials)

The distance estimated by participants was considered as one dependent variable. The real distance (correct answer) was measured by the Weather Scope software. On the software interface, clicking one point and dragging to another point, then the line between the two points indicated how many nautical miles the distance, where the change of distance (Δ) is calculated by: Δ = estimated distance - real distance. If Δ is small, then participants were making good weather-related distance judgment, conversely, if Δ is large then the participants made a poor weather-related distance judgment. If the Δ is negative, participants underestimated the distance, and if Δ is positive then participants overestimated the distance. So Δ would be the other dependent variable.

6.6.3 Procedure

Participants completed a demographic questionnaire and weather knowledge survey before the experiment. The experiment included training and test phase. And the task was the same in both phases. In the training phase, the experiment was explained to the pilots and they were given a rough idea of how they would estimate distance and learned the whole procedure of experiment. The whole procedure took about 45mins to complete.

There were three steps in the experiment (see Figure 6.3). In the first step, participants were asked to click the current location denoted by a red point. In the second step, participants were asked to estimate the current distance between the red point and the nose of the aircraft. In the third step, participants were asked to estimate the distance between the storm cell and the aircraft 15 min into the future. One possible condition where the shape of the storm was changing and the point would disappear was considered in the experiment. In this condition, the closest point of red area to the aircraft and estimated the distance.

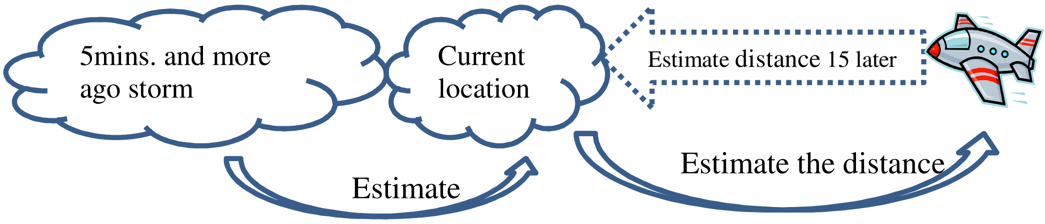


Figure 6.3 Task sequence of the experiment

Figure 6.4 illustrated the image that is given to the participants during the first step of the experiment. On the page of the first step, there was a marked point: X. Based on the storm speed and direction, marked point, and amount of time delay (timestamp denoted), participants estimated the current location by clicking on the image. After clicking on the radar image, a red point was shown on the page to denote the current location. On the page of the second step (see Figure 6.5), participants estimated the distance between the red point and the nose of aircraft and filled in the blank with their estimate. Participants also adjust the sliders to record their confidence in the estimation and their opinion of the safety for the estimated distance. After finishing the second page, participants clicked OK button and turned to the third page (see figure 6.6). On the third page, participants estimated the distance between the red point and the nose of the aircraft after 15 min based on the direction and speed of storm and the current distance. It was assumed that the speed of the aircraft was 120 knots and the storm would not dissipate during the 15 min. Participants filled in the blank with an estimated distance and used the slider to record their confidence in the estimate and their opinion of the safety for the estimated distance.

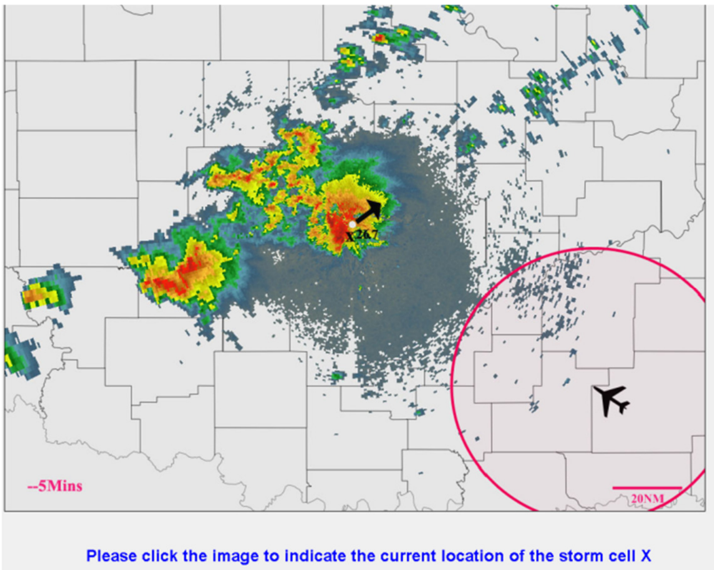


Figure 6.4 The first step page of the experiment

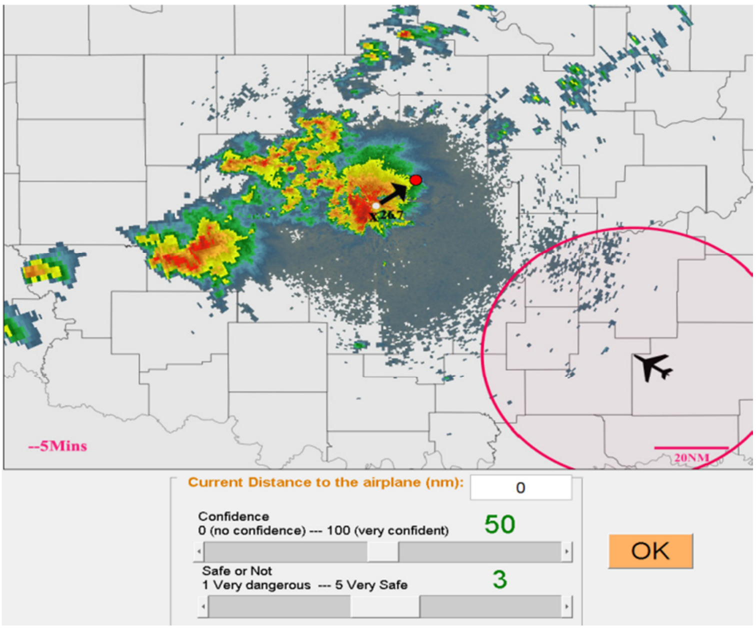


Figure 6.5 The second step page of experiment

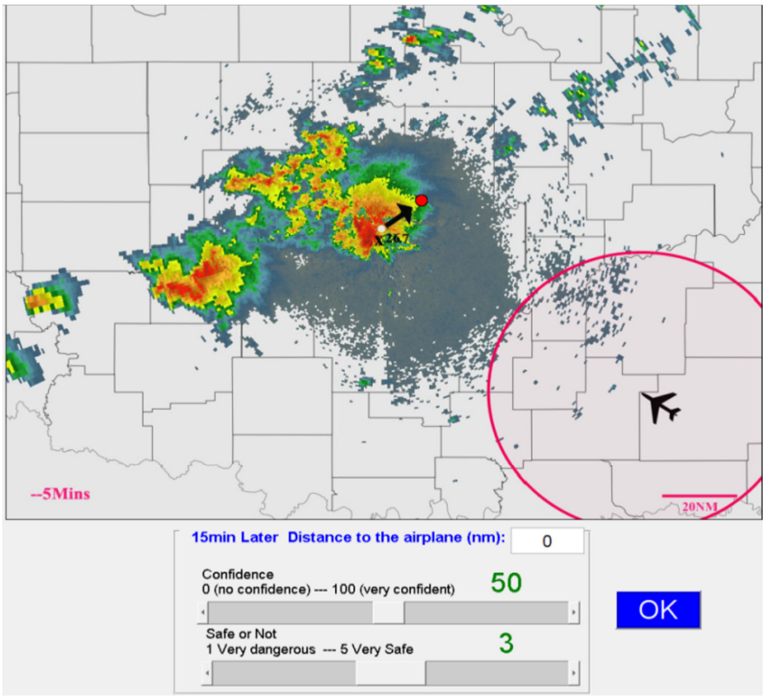


Figure 6.6 The third step page of experiment

Data were automatically recorded by the program. After completing the distance estimation task, the participants then completed several post-test questionnaires. The questionnaires focused on the pilots' situation awareness, their recollection of specific weather-related details, and their evaluation of the usefulness of the weather display.

6.7 The First Step--Current Location Estimation

The first step of the task was to click the current location of the marked point, X, based on the speed, direction and time stamp of the thunderstorm cells. After participants clicked the image, the pixel coordinate (x, y) were automatically recorded by the program. Based on the pixel coordinate, distances between the marked point, clicked point and true point were computed. The formula is as follows: the marked point, X, represented the past location already given on image; the clicked point represented the current location estimated by the participants, and the true point represented the true current location of the marked point. The distance is the length that storm cells have moved during the amount of time delay.

$$b=\sqrt{(x1-x2)^2+(y1-y2)^2}$$

The distances are denoted as "a", "b", and "c". "b" is the distance that participants estimated and "c" is the true distance that the storm had moved during the amount of time delay (see Figure 6.7). The units of the three points were pixels on the radar image so we converted the pixel unit to nautical miles (nm, hereafter) based on the scale on the images.

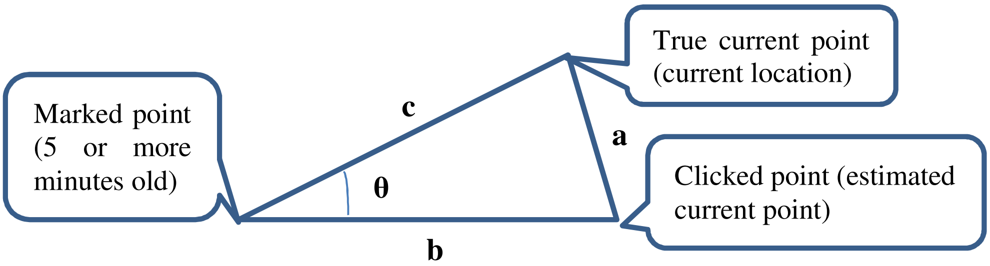


Figure 6.7 Three points and the distance

The relationship among the three lines could be denoted by the formula:

$$a = \sqrt{b^2 + c^2 - 2 \times b \times c \times \cos(\theta)}$$

where "a" is the deviation between "b" and "c". If θ is zero, "a" will be the difference between "b" and "c", which is Δ = b - c. The results showed that θ ranged from 0.3° to 3°. The angle, θ, was not used as a dependent variable because it was very small and related to the distance deviation, "a", based on the formula. The dependent variables included "a" and "b".

6.7.1 Effect of Movement Speed, Display, Time Delay on "b"

The estimated distance (b) that the storm moves during the amount of time delay was used as a dependent variable. Therefore, "b" was used to know whether participants could estimate the current location of a storm and be sensitive to the manipulation of movement and time delay. We used 2 (display) × 3 (movement) × 3 (time delay) designs to examine the sensitivity to the factors. A repeated measures ANOVA indicated that there was a significant distance difference between two displays ($F(1, 29) = 6.94$, $p = 0.013$), across three movement speeds ($F(2, 58) = 36.98$, $p < 0.001$) and three amounts of time delay ($F(2, 58) = 106.248$, $p < 0.001$).

When the storm movement speed was slow (b=10.15NM, c=5.83NM) and medium (b=12.26NM, c=10.67NM), participants tended to overestimate the distance (see Figure 6.8). When the movement speed is fast (b=14.46NM, c= 19.01NM), participants tended to underestimate the distance. Participants were sensitive to the movement speed.

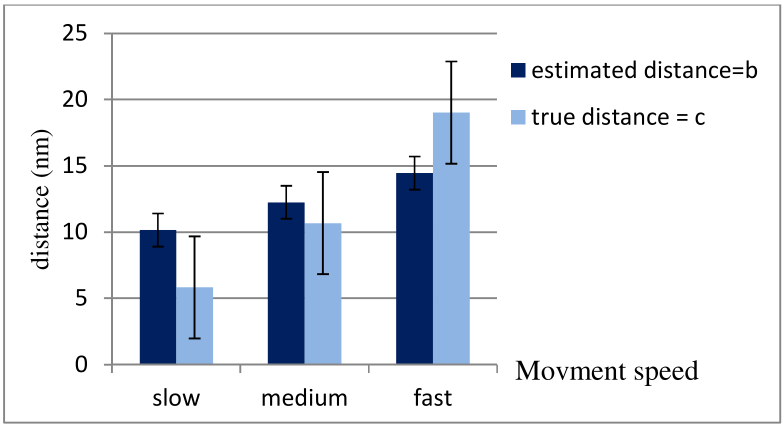


Figure 6.8 The estimated distance and true distance in movement speed

During the long time delay, participants underestimate the storm movement to be 17.01NM relative to the true distance of 17.83NM. When the time delay was short (b=8.69NM, c=7.13NM) and medium (b=11.16NM, c=10.55NM), participants overestimated the distance (see Figure 6.9.).

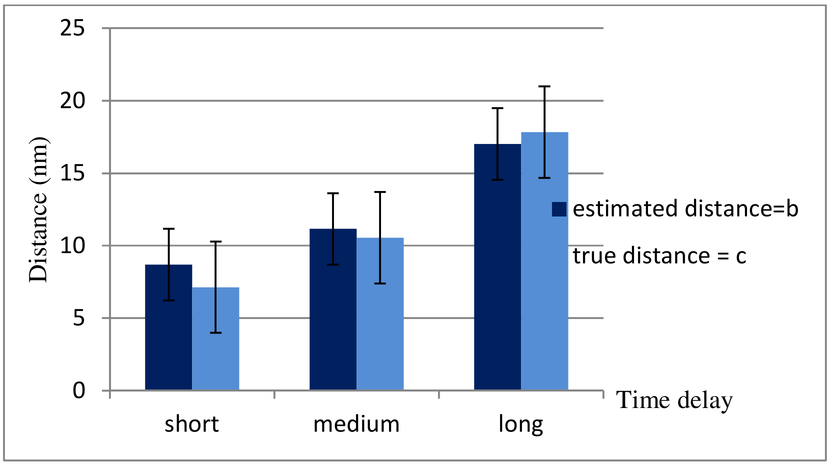


Figure 6.9 The estimated distance and true distance across the three time delay

Different types of display also resulted in different estimation. Participants underestimated distance when viewing animation, while viewing a static image made participants overestimate the distance (see Figure 6.10). The results showed that participants could distinguish the different levels of time delay and movement speed. Time delay did affect the distance estimation. However, the estimation of participation is very conservative.

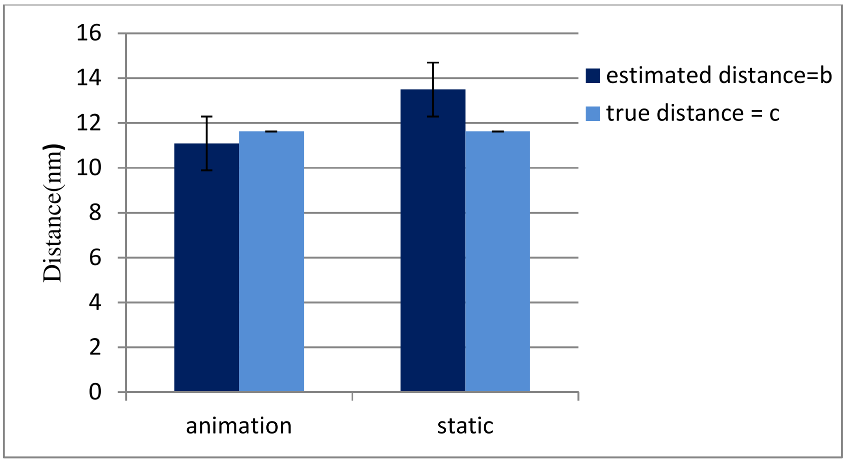


Figure 6.10 The estimated distance and true distance in two displays

Significant interaction existed between the types of display and time delay ($F(2, 58) = 3.372$, $p = 0.041$), between movement speed and the time delay ($F(4, 116) = 6.693$, $p < 0.0001$), between display and movement speed ($F(2, 58) = 13.87$, $p < 0.001$), and among display, movement and time delay ($F(4, 116) = 14.377$, $p < 0.001$). When time delay was long and storm movement was medium and slow, the estimated distance using animation was larger than the static image. Under other conditions, the estimated distance using animation is smaller than using static image (see Figure 6.11). The corresponding average estimated distance is listed in the Table 6.2:

Table 6.2 Means of distance across levels of display, movement, and time delay

		Display=animation (NM)	Display=static image(NM)
Speed=slow (20-35 knots)	Delay = S	6.24	9.40
	Delay = M	8.92	8.91
	Delay = L	14.38	13.05
Speed=medium (35-50 knots)	Delay = S	6.71	9.35
	Delay = M	10.14	13.26
	Delay = L	17.79	16.30
Speed=fast (above 50 knots)	Delay = S	7.75	12.73
	Delay = M	12.05	13.67
	Delay = L	15.83	24.75

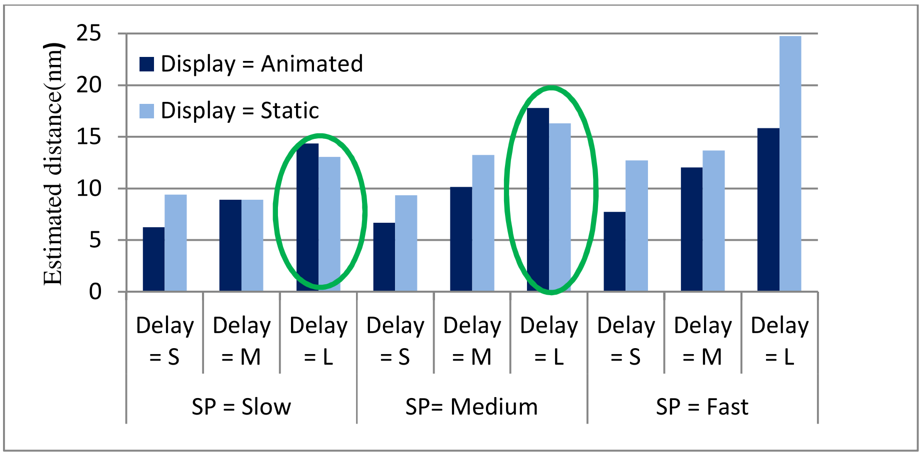


Figure 6.11 The interaction among display, movement, and time delay

In summary, types of display, storm movement speed, and amounts of time delay did affect participant's distance estimation. And participants have the capability to estimate the current location of a storm based on the animation and static image displays. Participants were sensitive to the different levels of movement speed and amounts of time delay, however, they had a low level of sensitivity.

6.7.2 The Effect of Movement Speed, Display, Time Delay on "a"

We used "a" as the dependent variable to investigate the estimated deviation between "b" and "c". We examined the effects of amount of time delay, storm movement speed and type of display on the distance deviation using 3 (time delay) x 3 (movement speed) x 2 (display) design. Under each combination of all levels of factors, there were three pure replication trials that used three different weather scenarios (see Table 6.3). So we used the average distance deviation to be the dependent variable. Repeated measures ANOVA indicated that the movement speed ($F(2, 58) = 46.044$, $p < 0.001$, $\eta^2 = 0.61$) and the amount of time delay ($F(2, 58) = 57.194$, $p < 0.001$, $\eta^2 = 0.64$) significantly affected the distance deviation with the ANOVA means shown in the Table 6.3. The effect size, η^2, was also computed for each significant effect to show the contribution to the variability of the data. The results showed that pilots had the ability to estimate the distance based on the time delay and movement speed. However, the display types didn't significantly affect the distance deviation.

Table 6.3 ANOVA table for the repeated measures (using SPSS and SAS)

	Average of the Cases (SPSS)		**Case one (SAS)**		**Case two (SAS)**		**Case three (SAS)**	
	F	**p**	**F**	**p**	**F**	**p**	**F**	p
Movement speed	46.044	<0.001	21.91	<0.0001	2.16	0.117	88.8	<0.0001
Time delay	57.194	<0.001	10.20	<0.0001	58.16	<0.0001	58.71	<0.0001
Display type	0.071	0.792	4.54	0.036	17.38	<0.0001	1.08	0.300
Move × delay	6.399	< 0.001	11.78	<0.0001	7.45	<0.0001	49.47	<0.0001
Move × display	0.019	0.981	0.05	0.95	12.33	<0.0001	8.95	0.0002
Delay × display	1.043	0.359	0.57	0.567	1.48	0.227	0.60	0.546
Move × delay × display	9.698	<0.001	4.02	0.0032	6.36	<0.0001	1.0	0.405

The individual weather case was computed to check the effect of three factors. When using the individual weather case, the type of display affected the distance deviation significantly in case one and two (see Table 5.3.). There was a significant interaction between the display and movement speed in case two and three. However, the direction of the significant difference was not the same across the three weather cases, so the average of three cases was used. Regardless of computation methods, movement and time delay significantly affected the distance deviation. Post Hoc test showed that when movement is fast the distance deviation (M = 11.2NM, SD = 1.68) is much higher than slow (M=6.5NM, SD = 2.74) and medium movement (M = 7.28NM, SD = 2.82). There is no significant difference between slow and medium movement (see Figure 6.12). For the amount of time delay, Post Hoc test showed that when time delay was long the distance deviation (M=11.16NM, SD =1.83) was much higher than short (M=6.8NM, SD = 2.98) and medium (M = 7.02NM, SD = 2.12) time delay ($p < 0.001$). There was no significant difference between the short and medium time delay.

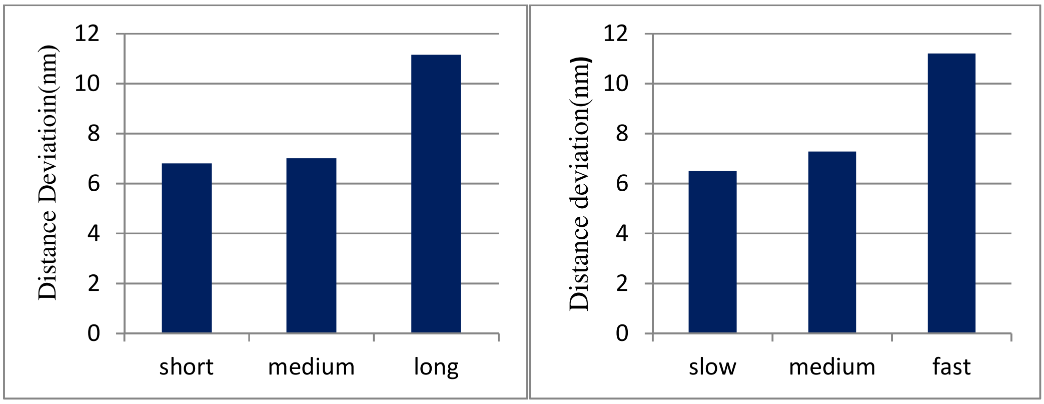


Figure 6.12 Distance deviation difference across three levels

There was a significant interaction (F (4, 116) = 6.399, $p < 0.001$) between movement speed and time delay (see Figure 6.13). When the thunderstorm movement speed was slow or fast, there was no significant difference in distance deviation between the short (M = 5.06NM, SD = 3.185 or M = 9.28NM, SD = 2.46) and medium time delay (M = 4.74NM, SD = 2.44; M = 8.95NM, SD = 1.83). However, when the movement speed was medium, the distance deviation of medium time delay was higher than the short time delay. It meant that when movement was medium, participants can distinguish the difference between the short (M = 5.46NM, SD = 4.08) and medium (M=7.36nm, SD = 3.88) time delay and make accurate current location estimations with short time delay.

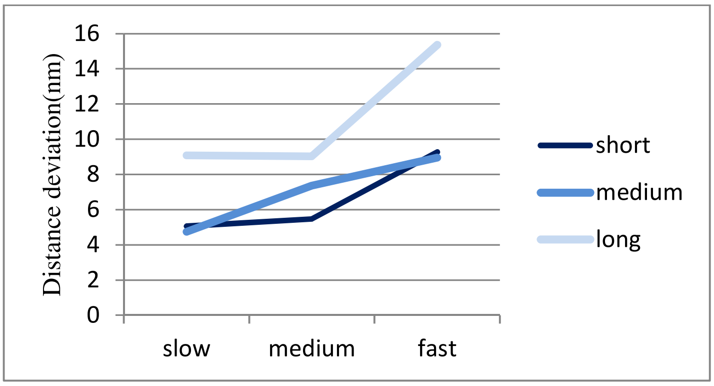


Figure 6.13 The interaction between the movement speed and time delay

The significant interaction among display, movement, and time delay showed different trends of each level (see Figure 6.13). When the storms move fast and time delay was long, the participants make more accurate location estimations using animation display (M = 13.51NM, SD = 3.4) than using static radar images display (M = 17.24NM, SD = 3.87). However, when storms move fast and the time delay is short, participants make more accurate location estimations using static image (M = 7.58NM, SD =5.34) than using animation (M = 10.98NM, SD= 0.79). In contrast, when the storms move slowly and time delay was short, participants make more accurate location estimations using animation (M = 4.71NM, SD = 2.52) than using static radar images (M = 6.62NM, SD = 4.28). When the storm movement speed was medium, there is no difference in the location estimation between the static image and animation with short and medium time delay.

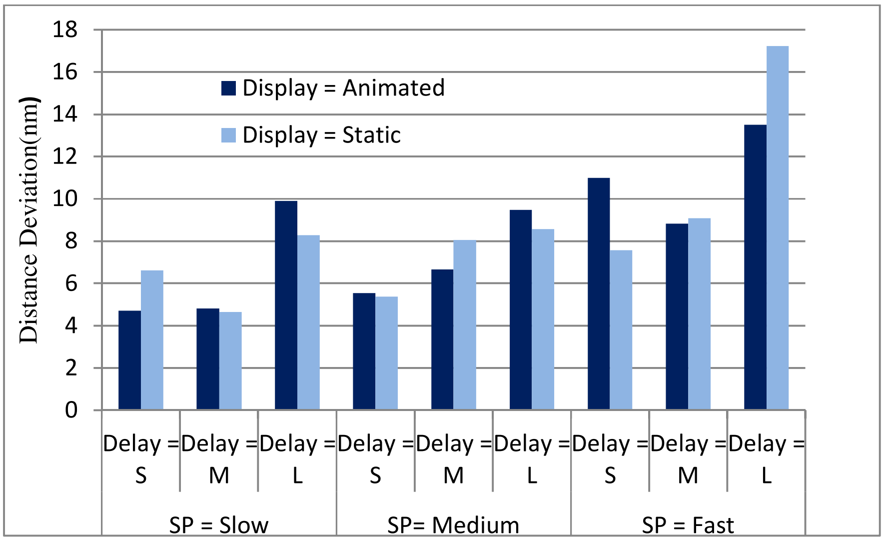


Figure 6.14 The interaction among display, movement speed and time delay

Distance deviation represented the error of the distance estimation. The significant effect of movement speed and time delay suggested that the difference between line "b" and "c" was significant. The deviation was small when the movement was slow and medium, similar to when time delay was short and medium. It is difficult for participants to estimate the current location and the deviation could be up to 16NM when a storm moves fast and time delay is long.

The estimated distance also represents whether participants could use animation to denote the correct directions of storm movements. Static images with speed arrows don't show more accurate location estimations than animation. The interaction shows that participants could correctly determine the storm movement direction. Animation seemed to be difficult for participants to estimate only when time delay was long and movement was fast.

6.7.3 Discussion

Based on the formula: distance = time × speed, the time and speed affect the distance. This formula is objective and the relationship between time and speed is also objective. However, in the experiment, the location is estimated by participants based on the amount of time delay and storm movement speed. If the movement speed and time wouldn't affect the distance results, it is shown that participants don't have the ability to estimate the distance.

The results showed that the movement speed, the amount of time delay, and types of display significantly affected the location estimation. Participants have the ability to estimate the distance and are sensitive to the time delay and movement speed. Time delay effect sometimes depends on the storm speed because of interaction.

Table 6.4 Location Estimation Results

Movement Speed	**Location Estimation**	**Accuracy**	**Time delay**	**Location Estimation**	**Accuracy**
Slow	Overestimate	High	**Short**	Overestimate	High
Medium	Overestimate	High	**Medium**	Overestimate	High
Fast	Underestimate	Low	**Long**	Underestimate	Low

In the table 6.4., movement speed is specified into two levels: fast level; slow and medium level. The amount of time delay is also specified into long level and medium and short level. Participants could process medium and slow movement speed, and medium and short time delay easily since accuracy of slow movement and short and medium time delay is the highest. Participants could not distinguish the difference between slow and medium movement, short and medium delay. It is difficult for participants to process the long time delay and fast movement since the accuracy of the location estimation is the lowest, which supported hypothesis two. When the movement is at medium speed, the short time delay is more accurate than the medium time delay.

Types of displays directly affect current location. Using animation, participants underestimated the current location of storm. The condition was different when using static images. Also types of displays interact with movement speed and amounts of time delay. Most of time, the accuracy of animation is higher than static image. However, when delay is long and movement is slow or time delay is short and movement is fast, static is higher than animation.

6.8 The Second Step--The Current Distance Estimation

The second step of the task was to estimate the current distance between the clicked point and the aircraft. The aircraft was assumed to be at the current location. Estimated distance and the difference between the estimated distance and true distance were used as the dependent variables because the angle between the two dash lines may be very small (see Figure 6.15),

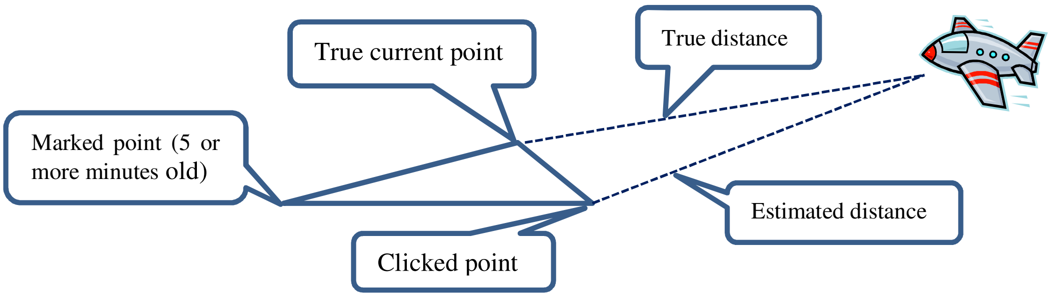


Figure 6.15 The distance between the clicked point and airplane

Distance estimation was not an individual task because the time delay effect would propagate into the distance between the storm and the aircraft. The effects of amount of time delay, storm movement speed and type of display were examined using 3 (delay) x 3 (movement speed) x 2 (display) factor design as an indicator of sensitivity of the participants to the current distance estimation.

6.8.1 Effect of Movement, Time Delay, Display on Estimated Distance

The repeated measures of ANOVA indicated that movement speed ($F(2, 60) = 242.915$, $p < 0.0001$) and the amount of time delay ($F(2, 60) = 101.388$, $p < 0.001$) significantly affect the current distance estimation. Participants seem to underestimate the distance between the storm and the aircraft (see Figure 6.16). The display type did not significantly affect the distance estimation.

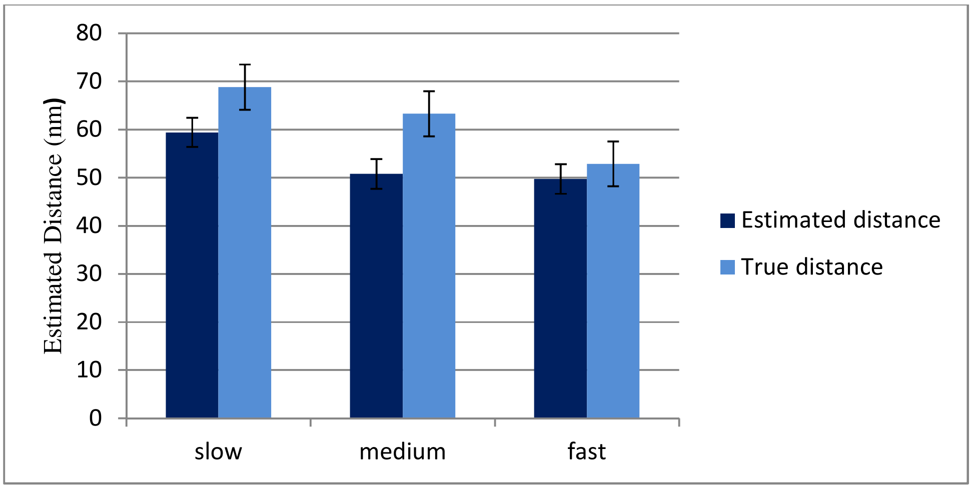


Figure 6.16 The comparison between the estimated and true distance

There was a significant interaction between display and time delay ($F(2, 60) = 3.379$, $p = 0.041$), between movement speed and time delay ($F(4, 120) = 200.484$, $p < 0.0001$), and among display, movement speed, and time delay ($F(4, 120) = 92.356$, $p < 0.0001$). When time delay was short, the distance estimation using animation was larger than using a static image. When the movement was slow and time delay was short, the distance estimation was much larger than other conditions (see Figure 6.17.).

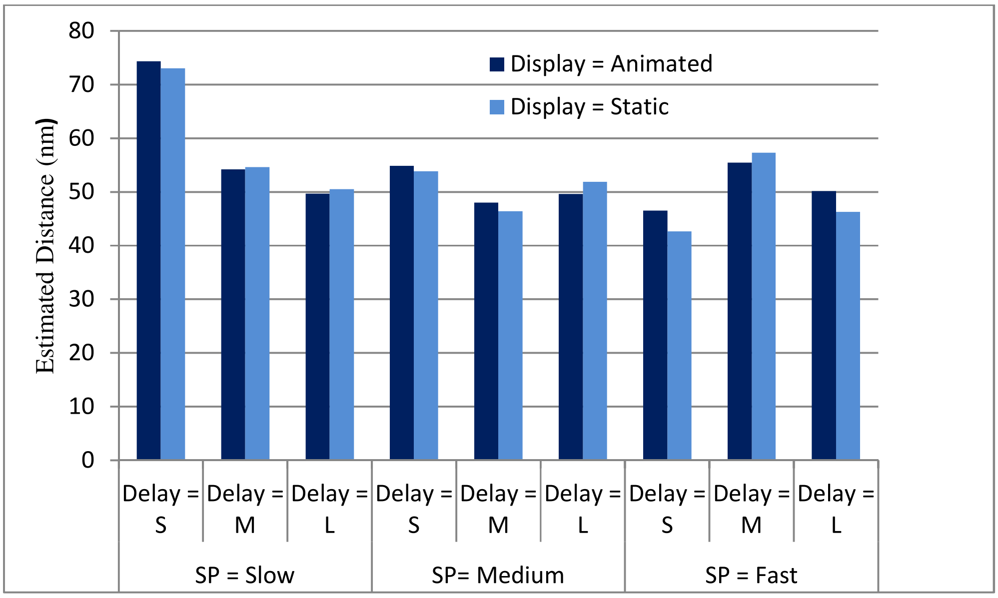


Figure 6.17 The distance interaction among three factors

6.8.2 Effect of Movement, Time Delay, Display on Distance Difference

The effects of amount of time delay, storm movement speed and type of display on the distance difference between the estimated distance and the true distance were examined using 3 (time delay) × 3 (movement speed) × 2 (display type) factor design. The repeated-measures of ANOVA (see Table 6.5.) indicated that the amount of time delay ($F(2, 60) = 64.195$, $p < 0.001$, $\eta^2 = 0.897$) and the movement speed of storm cells ($F(2, 60) = 262.174$, $p < 0.001$, $\eta^2 = 0.682$) significantly affected the distance estimation of participants. There is no significant difference between two types of display ($F(1,30) = 0.801$, $p = 0.378$). Post Hoc test shows that if the storm cell moves fast, the distance estimation will be more accurate (M = -3.061, SD = 0.839) than slow movement (M = -

7.99, SD = 0.835). The storm cells with medium speed are the most difficult to estimate (M = -14.04, SD = 0.932) (see Figure 6.18), where participants underestimate the distance.

Table 6.5 ANOVA table for the distance difference (using SPSS and SAS)

	Average of the Cases (SPSS)		**Case one (SAS)**		**Case two (SAS)**		**Case three (SAS)**	
	F	**p**	**F**	**p**	**F**	**p**	**F**	p
Movement speed	262.17	< 0.001	62.97	<0.0001	6.13	0.002	222.9	<0.0001
Time delay	64.19	<0.001	45.32	<0.0001	32.17	<0.0001	162.8	<0.0001
Display type	0.80	0.38	0.05	0.83	3.34	0.065	0.25	0.62
Move × delay	47.24	< 0.001	20.41	<0.0001	4.18	0.016	18.10	<0.0001
Move × display	2.84	0.066	3.57	0.029	3.47	0.032	1.13	0.32
Delay × display	4.02	0.02	2.23	0.11	3.93	0.020	1.22	0.29
Move × delay× display	5.27	0.001	2.24	0.11	3.15	0.044	0.26	0.77

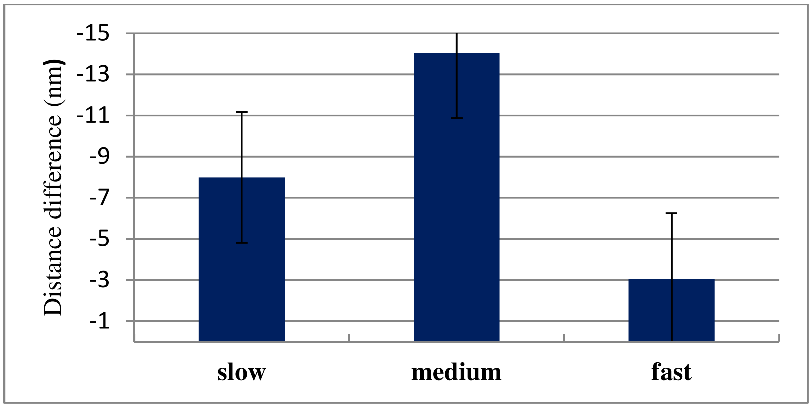


Figure 6.18 The distance difference in movement speed

Post Hoc Test indicated that if the amount of time delay is long, the distance estimation is more accurate (M= -4.708, SD = 1.017) than short (M = -10.461, SD = 0.821) and medium (M= -9.922, SD = 0.804) amount of time delay. The short time delay is more difficult for the distance estimation than medium and long time delay (see Figure 6.19).

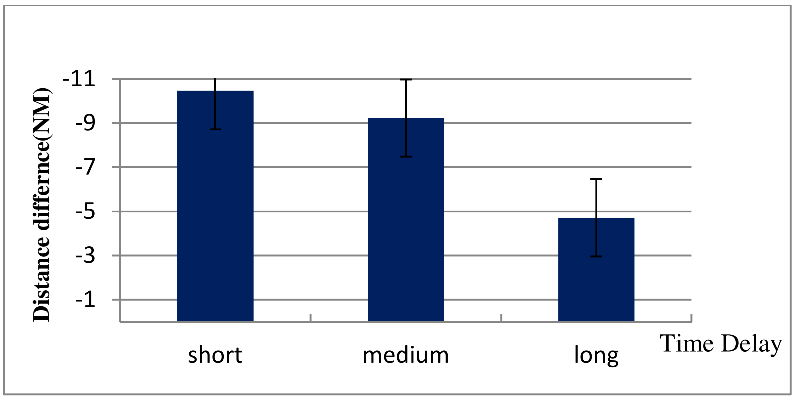


Figure 6.19 Distance difference in time delay

There was also a significant interaction between the amount of time delay and the movement speed ($F (4, 120) = 47.235$, $p < 0.001$, see Figure (6.20)). No matter how fast the storm moves, the longtime delay caused the most accurate distance estimation (see Figure 5.18). Similarly, no matter how long the time delay was, participants can make the most accurate estimation when the speed was fast. The medium storm movement with medium amount of time delay has the least accurate distance estimation (M = -20.895, SD = 0.949) compared to other amounts of time delay. If the storm moved fast, it was easier for participants to estimate distance than when the movement was slow. When the storm moved slowly, the short time delay had the least accuracy compared to the long and medium time delay.

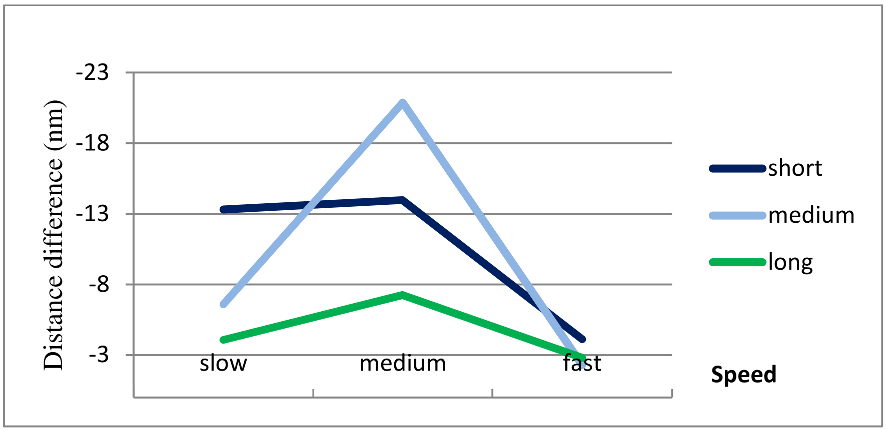


Figure 6.20 The interaction between movement speed and time delay

There was a significant interaction between the display types and time delay (F (2, 60) = 4.022, p = 0.023) (see Figure 6.21). When the time delay was medium and long, there was no significant difference between animation and static image. However, when the time delay was short, animation helped the participant make more accurate estimations than a static image.

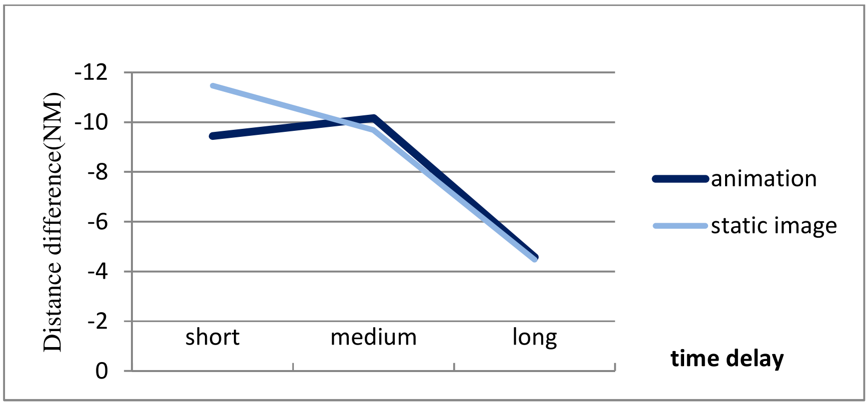


Figure 6.21 The interaction between the display and time delay

There was a significant interaction among display, movement speed and time delay (F (4,120) = 5.270, p = 0.001, see Figure 6.22.). When the time delay was medium and short, there was no different for static image and animation across three levels of movement. For the long time delay, when the movement was fast, animation display helps participants make more accurate estimations than a static image. And when the movement was slow and medium, the static image makes more accurate estimations than animation.

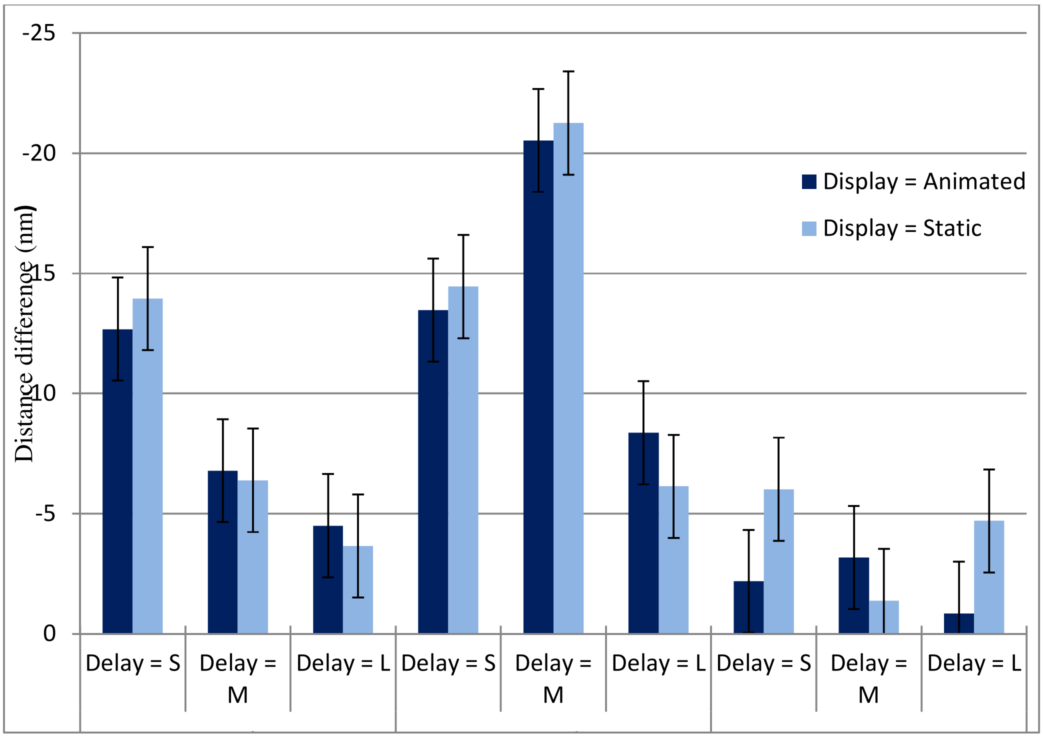


Figure 6.22 The interaction among display, speed, and time delay

Under animation display condition, in order to know the speed and direction of a storm cell accurately, participants needed to replay the animation. We recorded the number of times replaying. The speed of storm cells ($F (2, 60) = 10.628$, $p < 0.0001$) and amount of time delay ($F (2, 60) = 6.104$, $p = 0.004$) significantly affect the number of times that participants replay. If the storm cells move slowly, participants replay two times ($SD = 0.14$) while participants need to replay 3 times on average ($SD = 0.188$) if the speed of storm cells is medium and fast. If the time delay is long, participant still need to replay three times (SD = 0.19) otherwise they click the replay button two times. It was shown that long time delay and fast movement were more difficult for participants to process the direction and speed.

Generally we used the average of three cases of each level of independent variables. To avoid the bias created by the data average, we compared the levels of individual case and the results are similar to the average. The only difference is that we see several cases in fast movement level have positive distance estimations that mean participants overestimated the distance about 4 - 12 NM. In other words, if the storm cells move fast, like a tornado, participants overestimated the distance between the storm cell and the aircraft more easily than slow movement. On the other hand, the static image with speed arrow has the same function as the animation since there is no significant difference between them. However, 29 out of 31 participants prefer the animation as the weather display. The reason is that animation can tell the spatial development of storm. The static image only could tell the direction and speed of storm. Participants need to do mental computation to know the distance so it is difficult for them to estimate the distance if the time delay is short. Some participants suggested that the display will be more intuitive if each frame of animation denoted the speed and direction of storm cells.

6.8.3 Confidence and safety evaluation for the distance estimation

Participants were asked how sure they were for the distance estimation. The confidence scale ranged from zero (without any confidence) to 100% (very confident). The results showed that participants have high confidence (M = 80.1%) when they estimate the current distance between a thunderstorm and the aircraft. The storm movement speed and the amount of time delay had no significant effect on the confidence evaluation. For the different types of display, animation or static image, confidence didn't show any difference. Participants always have high confidence when they estimate the distance.

After estimating the distance, participants need to identify whether the distance is safe for the aircraft or not. There are five levels for the safety evaluation, 1--very dangerous, 2---dangerous, 3--neutral, 4----safe, 5---very safe. We set all the current distances as very safe, so the safety rank is four. Repeated measurement ANOVA showed that the types of display didn't make any difference for the safety rank ($F (1, 30) = 0.29$, $p = 0.595$). For the movement speed, there is a significant difference in safety rank among three levels ($F (2, 60) = 32.480$, $p < 0.001$). For the amount of time delay, participants have significantly different ranking ($F (2, 60) = 34.813$, $p < 0.001$) among three levels.

Since the safety rank is based on the distance estimation and participants underestimate the distance, the safety rank also is lower than the correct rank. Post Hoc test shows that medium ($M = 3.6$, $SD = 0.173$) and fast ($M = 3.57$, $SD = 0.157$) movement speed results in lower safety ranking than slow movement ($M = 4.014$, $SD = 0.158$). While long time delay has the lowest safety ranking ($M = 3.5$, $SD = 0.159$) compared to the medium ($M = 3.76$, $SD =0.164$) and short ($M = 3.9$, $SD = 0.161$) time delay.

There is a significant interaction between time delay and movement ($F (4,120) = 18.257$, $p < 0.001$, see Figure 6.23). When the movement is fast, long time delay will result in low safety ranking while medium time delay results in high safety ranking. When the movement speed is slow, the short time delay results in high safety ranking. When the movement is medium, the medium time delay has the low safety ranking while the safety ranking is high when the speed is slow and fast.

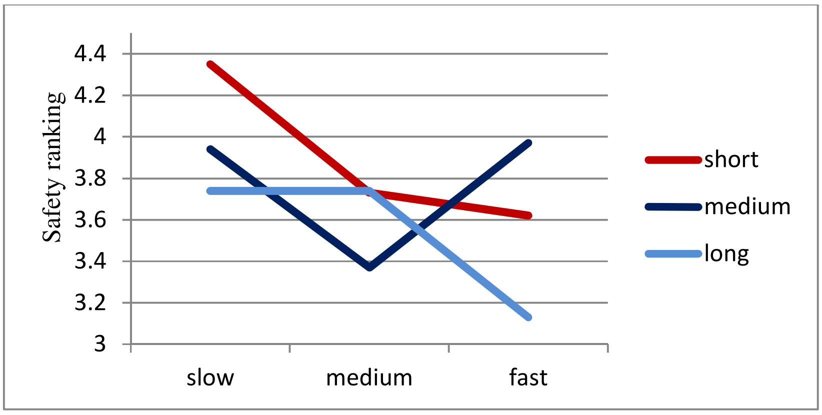


Figure 6.23 Interaction between the movement and time delay

6.8.4 Response Time

Response time is counted from the clicking to the end of the current distance estimation. Repeated-measure ANOVA indicates that display type, movement speed and amount of time delay does not significantly affect the response time. However, there is a significant interaction ($F (2, 58) = 3.22$, $p = 0.047$) between display and movement speed (see Figure 6.24.). Using static image, participants' response is quicker than using animation when the storm movement is fast. However, when the movement speed is slow, participants' response is slower using static image than using animation.

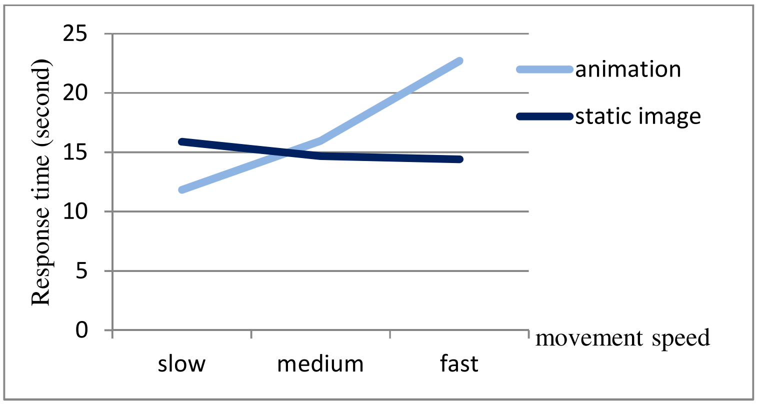


Figure 6.24 The interaction between the movement speed and display type

6.8.5 Discussion

Movement speed and time delay significantly affected the current distance estimation. However, the relationship between the movement speed and time delay is different from the location estimation (see Table 6.6). For the movement speed, the accuracy of fast movement is higher than slow and medium movement. The accuracy of medium speed is the lowest and is difficult for participants to estimate. For the time delay, the accuracy of long time delay is higher than the short and medium time delay. The accuracy of long time delay and fast movement is the highest.

Table 6.6 Current distance Estimation Results

Movement Speed	**Estimation Error**	**Accuracy**	**Time delay**	**Estimation Error**	**Accuracy**
Slow	Underestimate	low	**Short**	Underestimate	Low
Medium	Underestimate	lowest	**Medium**	Underestimate	Low
Fast	Underestimate	Highest	**Long**	Underestimate	Highest

The display types, animation or static image doesn't significantly affect the current distance estimation. Animation display, in general, supports the fast movement and longtime delay or slow movement and short time delay. Static image display supports the fast movement and short time delay or medium time delay and slow movement. Animation display supports the short time delay much better than static image display. Actually, animation display needs to click three times or more and take much time to make accurate estimation. Using static image, participants' response is quicker than using animation when the storm moves fast.

For the safety ranking, long time delay and fast movement results in low safety ranking while slow movement and short time delay have higher safety ranking. All participants estimated the weather conditions with high confidence.

In the first step of the task, participants need to estimate the distance that storm move during the amount of time delay. The type of display directly affects the estimation and participant underestimate the distance by using animation display. For the following step, the display only significantly interact with time delay or movement speed.

The trend of movement speed, time delay and the interaction seems to be very different between the location estimation and distance estimation. The accuracy of long time delay and fast movement in location estimation is totally different in distance estimation. The big difference between the two estimations is the distance range. The location estimation ranges from 2nm to 20 nm while the current distance estimation ranges from 40nm to 100nm. In the small distance range, the location estimation seems to be much easier than the current distance estimation with large range. The other difference is that location estimation is directly influenced by the storm movement and amount of time delay whereas the influence on distance is indirect.

Participants need use the amount of time delay and storm movement to estimate the current location directly. In the second step of the task, participants only need to estimate the absolute distance between the storm and aircraft based on the scale and range ring without the use of time delay information. But why do the time delay and movement speed affect the current distance estimation? Base on the distance function of Proffitt et al. (2003), perceived distance is a function of distal extent and the anticipated effort to estimate the distance. The current distance estimation is one step of a serial task not an individual task. On the other hand, participants have the effort and expectation to complete the distance estimation task. From this point, we could explain the difference between Table 6.4 and Table 6.6. In the first step, participants learns that it is difficult to process the fast movement and the long time delay, so when they estimate the current distance between storm and aircraft, they are very careful and conservative to estimate when move is fast and slow and time delay is long.

The time delay affects the distance estimation, which shows that participants have the capabilities to integrate all the necessary information on the display to make spatial judgment. Although there is a relatively large and statistically proportion of variance that cannot be explained by the accuracy in the distance judgment task (Law, 1990), we still could figure out what it is. The variances come from point localization on the storm cell, which is not easy, resolution of animation and static image, true distance and location measures, and the weather scenarios.

6.9 The Third Step -- Future Distance Estimation

After estimating the current distance between the storm cell and the aircraft, participants need to estimate 15 minutes later the distance between the aircraft and storm cells based on the current condition, such as the storm movement speed and current distance. Based on the estimation, we could test the projection component of situation awareness of participant. We assumed the speed of aircraft is 120 knots and the distance that the aircraft fly in 15 minutes is 30 NM. Participants only need to estimate the distance that storm cells move in 15 minutes. The speed of storm cells is inducted from the animation or the speed arrow on the radar images.

6.9.1 Effect of Movement, Time Delay, Display on Distance Difference

Effect of movement and time delay on future distance estimation were investigated using 2 (display) × 3 (movement speed) ×3 (time delay) factor designs. Repeated measure ANOVA showed that the movement speed of the storm cells significantly affects the distance estimation ($F(2, 60) = 32.671$, $p < 0.0001$). The results seem to be reasonable, which the speed of movement actually affects the distance. The Post Hoc test indicates that when the storm move fast participants overestimate the distance (M = 1.527, SD = 1.106) while the participants underestimate the distance when the storms have slow (M = -4.86, SD =1.41) and medium speed (M = -3.23, SD = 1.217 see Figure 6.25). There is no significant difference between the two types of display, which means participants use animation and static images both could estimate the distance reasonably.

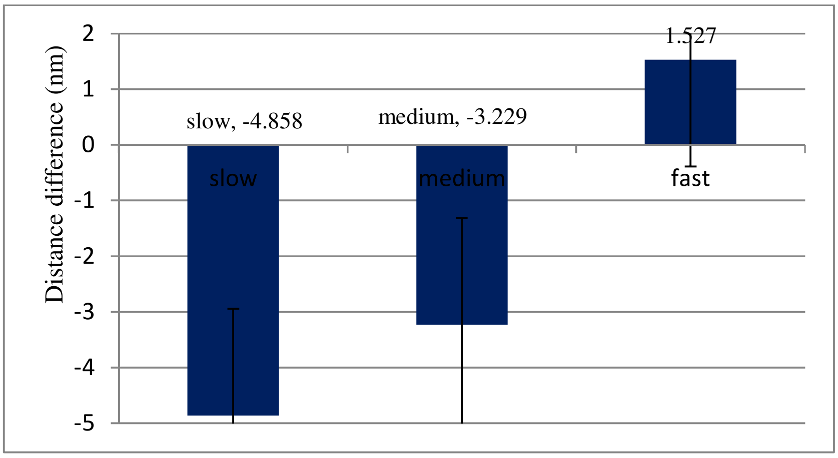


Figure 6.25 Distance difference in different level of movement

For the future distance estimation, the amount of time delay actually won't affect it because participants need not use the amount of time delay to estimate the distance of 15 minutes later. Still participants need to estimate the future distance based on the current location and current distance. The results show that the amount of time delay significantly affect the distance estimation ($F (2, 60) = 114.905$, $p < 0.001$). The Post Hoc test (see Figure 6.26) shows that participants underestimate the distance (M=-7.624, SD=1.280) when the time delay is short while the participant overestimate the distance when the time delay is medium (M=0.258, SD=1.188) and long (M=0.805, SD=1.161).

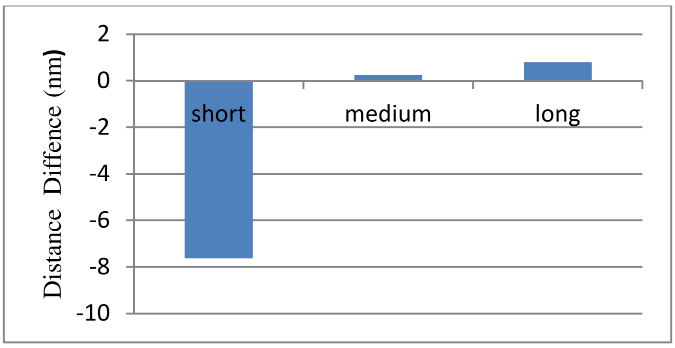


Figure 6.26 The distance difference among three levels of time delay

There was a significant interaction between the movement speed and amount of time delay (F (4, 120) = 35.86, p < 0.001). When the movement speed was medium, participants overestimated the distance in the medium time delay. When the movement speed was fast and slow, participants overestimated the distance in the long time delay (see Figure 6.27).

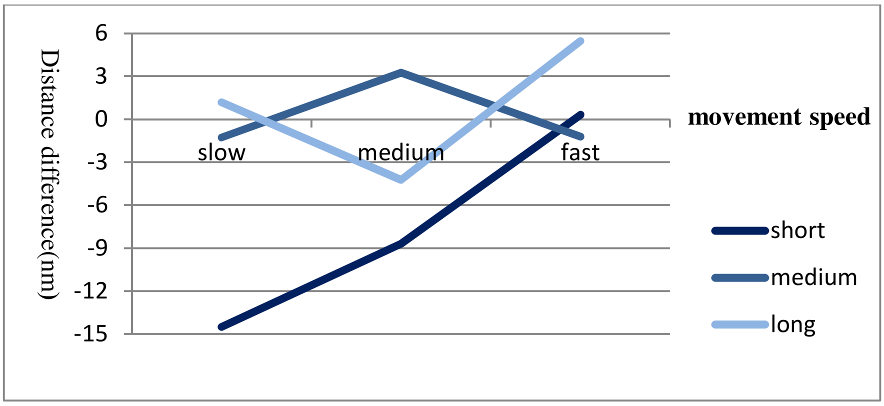


Figure 6.27 The interaction between movement speed and time delay

The significant interaction took place between the display types and time delay (F (2, 60) = 3.174, p = 0.049). For the medium time delay, animation seemed to better than static image display whereas the static image was better when the time delay was long (see Figure 6.28.).

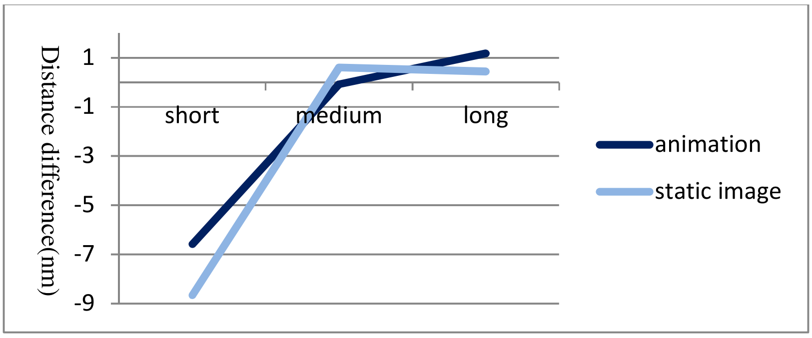


Figure 6.28 The interaction between display and time delay

6.9.2 Confidence and safety ranking

Repeated measure ANOVA indicated that there was no significant difference in confidence as for the display types, movement speed and amount of time delay. The average confidence was about 74%. After participant estimated the distance, participants need to identify whether the distance is safe for the aircraft or not. There are five levels for the safety evaluation, 1--very dangerous, 2---dangerous, 3--neutral, 4----safe, 5---very safe. We used the difference between the estimated ranking and the true ranking as dependent variable. The types of display didn't make any difference for the safety rank. For the movement speed, there was significant difference of safety rank among three levels ($F(2, 60) = 33.674$, $p < 0.001$). Post Hoc test shows that participants underestimate the safety level of slow movement ($M=-0.974$, $SD = 0.126$) more than fast movement ($M=-0.38$, $SD = 0.125$, see Figure 6.29). For the amount of time delay, participants have no significantly different ranking.

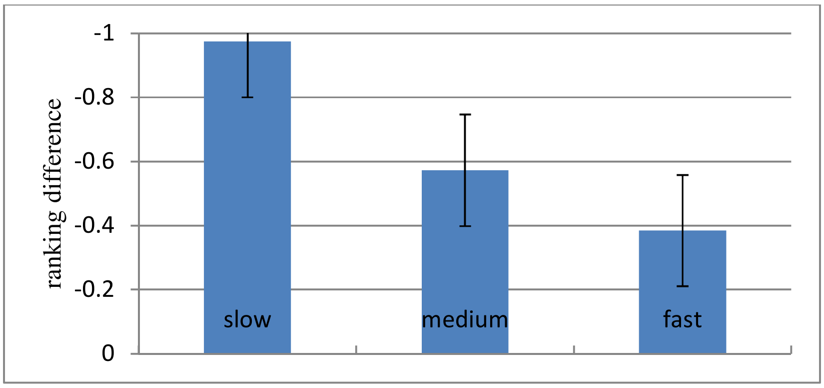


Figure 6.29 The ranking difference in movement levels

There was a significant interaction ($F(4,120) = 14.41$, $p < 0.001$) between movement and time delay (see Figure 6.30.). Since the safety rank was based on the distance estimation and participants underestimate the distance, the safety rank also is lower than the correct rank. When the storm moved slowly, participants tended to underestimate the safety. When the movement was fast, participants tended to overestimate safety correctly if the time delay is short whereas participants tend to underestimate safety ranking when time delay is medium.

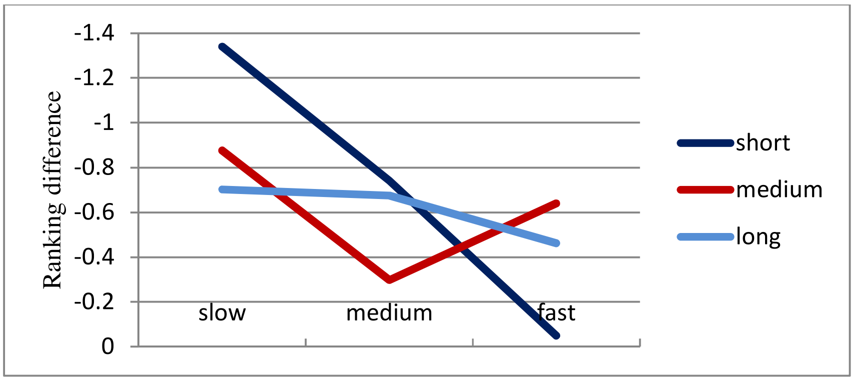


Figure 6.30 The ranking interaction between the movement and time delay

6.9.3 Response Time

Response time is counted from the second page appear to the completion of the future distance estimation. Still using 2 (display) × 3 (movement) ×3 (time delay) factor design, SPSS repeated measure indicates amount of time delay ($F (2, 58) = 6.2$, $p=0.004$) and display ($F (1, 29) = 8.564$, $p=0.007$) significantly affect the response time. The participants' response time is shorter (M=18.104s, SD = 1.272) than the static image (M=20.05, SD = 1.65). The movement speed doesn't significantly affect the response time. The Post Hoc test shows that response time in medium time delay is shorter (M = 17.68, SD = 1.42) than the short (M=20.304, SD = 1.61) and long (M = 19.25, SD = 1.46) time delay (see Figure 6.31).

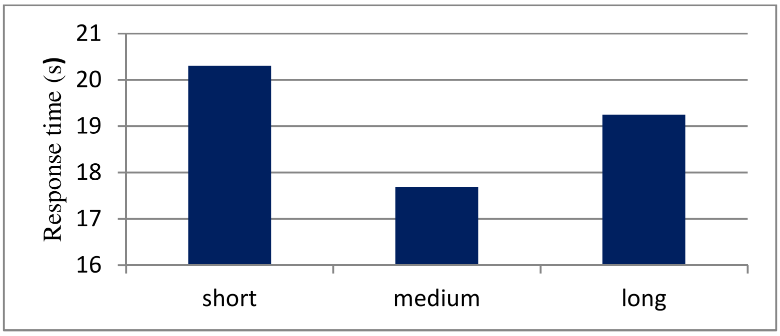


Figure 6.31 The response time in time delay

There is a significant interaction ($F(2, 58) = 17.937$, $p < 0.0001$) between display and movement speed (see Figure 6.32). When the movement is slow, participants' response is quicker using animation than using static image. When the movement is medium and fast, the participants' response is quicker using static image than animation.

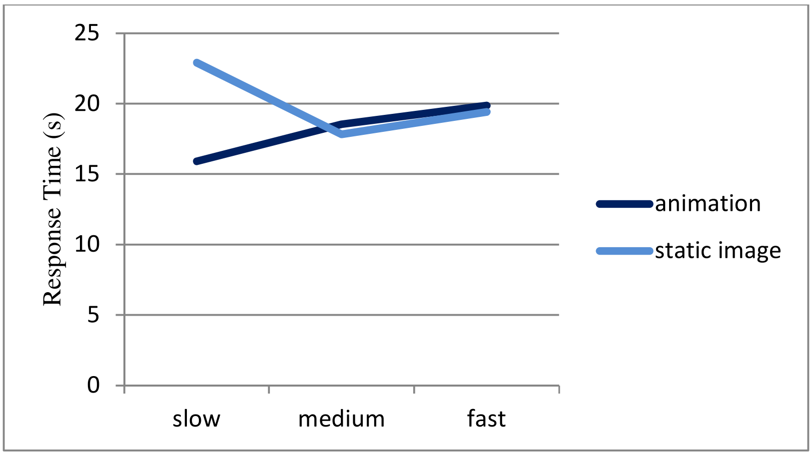


Figure 6.32 The interaction between the display and movement in response time

Also there is a significant interaction ($F(2, 58) = 7.935$, $p = 0.001$) between display and amount of time delay (see Figure 6.33). The trend is the same as the interaction between the display and movement. The movement speed and amount of time delay also significantly interacts ($F(4, 116) = 27.15$, $p < 0.0001$) (see Figure 6.34).

When movement is slow, short time delay makes participants response more slowly than medium and long time delay. However, short time delay makes participants quicker when the movement is medium and fast than medium and long time delay. Display types, movement, and time delay significantly interact ($F (4, 116) = 8.616$, $p < 0.0001$).

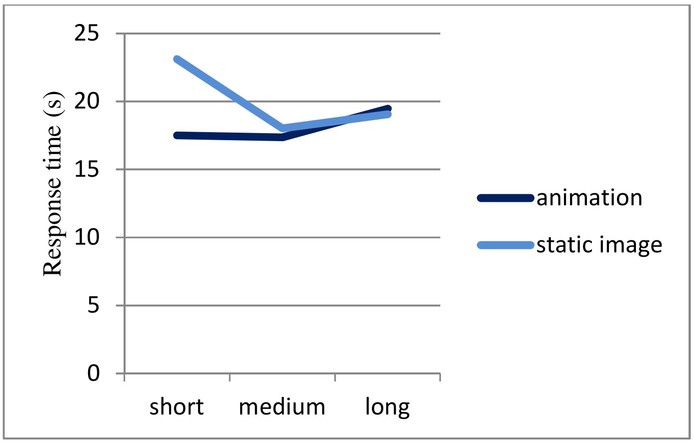


Figure 6.33 The interaction between the display and movement in response time

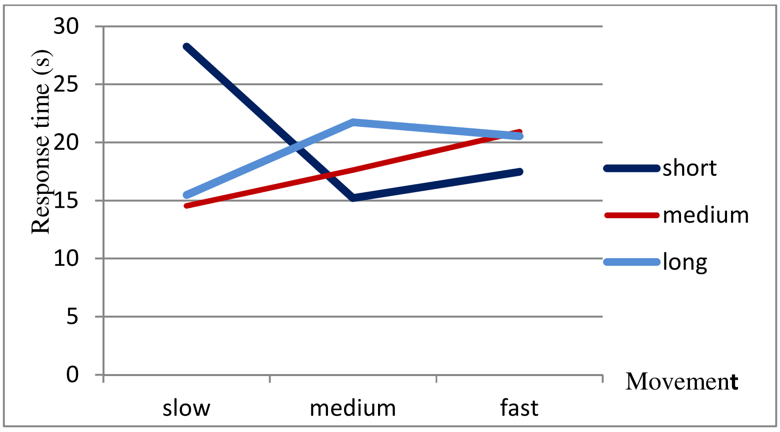


Figure 6.34 The interaction between the movement and time delay

6.9.4 Discussion

When the storm moved fast, participants tended to overestimate the 15-mins-late distance while participants tended to underestimate the distance when the movement is slow and medium. When the time delay is medium and long, participants will overestimate the distance while the participants will underestimate the distance under the short time delay. Under the short time delay and slow movement condition, participants underestimate the distance whereas participants overestimate the distance under medium movement and medium delay condition.

For the safety ranking, participants tend to underestimate the safety ranking when the movement is slow. The underestimation means participants rank the safety level as dangerous while the safety level is at least three (neutral) and more (safe or very safe). Although the fast movement also causes the underestimation, participants seem to be very cautious, which means participants' ranking is close to the true ranking. No matter what types of display, movement and time delay, participants estimate the distance with very high confidence, about percentage of 74.

For the type of display, when the time delay is medium the estimation of distance is better using animation than static image. When the time delay is long, static image seems to support the distance estimation better than the animation display. However, participants' response is quicker using animation than the static image especially when the movement is slow and time delay is short.

In this step, when time delay is short, participants estimate the future distance more accurately for the fast movement than the slow and medium movement. The interaction exists when the time delay is medium and long and movement is medium. When time delay is long and movement is fast, participants overestimate the distance too much. For the projection of future, participants were still very conservative.

The time delay or the age of radar image affects the projection component of weather situation awareness of pilots. In other words, the age of radar information affect the pilots' distance judgment. There are several factors affect the distance estimation, such as effort (Proffitt et al., 2003), effort-related factor (emotion or age) (Woods et al., 2009), and virtual environment (Takahashi et al., 2013). The extent of underestimated distance is greater with virtual environment than with real world environment (Jerome & Witmer, 2005), which could explain the underestimation of current distance.

6.10 After-test Questionnaire

6.10.1 Usability and Situation Awareness

After completing the task, participants need to fill the post-questionnaires to know how useful all the information, shown on the display, is. Participants like animation display more than static image ($t = 4.087$, $p < 0.0001$). They also think it is easier to estimate the distance according to animation than static image ($t = -2.15$, $p = 0.040$).

We used SART questionnaire to test situation awareness when using animation and static image. Using paired-compare T test, the results show that there is no significant difference between two types of display on each dimension, such as complexity, situation change, alert, attention, mental capacity and familiarity.

6.10.2 The Difference between the novice and experience pilots

Base on the flight hours, participants have been divided into two groups: experienced pilots (flight hours > 350) and novice pilots (flight hours <= 350). One-way ANOVA results showed that when the movement is slow and time delay is long, experienced pilots' estimation of the location is more accurate than novice ($F(1,55) = 6.285$, $p = 0.015$). However, when movement is medium and time delay is long, novice's estimation of location is more accurate ($F(1, 54) = 9.0$, $p = 0.004$).

For the current distance estimation, when the movement is fast and time delay is long, experienced pilots' estimation is more accurate than the novice($F(1,54) = 4.56$, $p = 0.037$). Most of time, there is no significant difference between experienced and novice participant. For the safety ranking, experienced participants' safety ranking is more close to the true ranking ($M = -0.2$, $SD = 0.97$) than novice ($M = -0.8$, $SD = 0.997$) when the movement is medium and time delay is medium ($F(1, 58) = 7.32$, $p = 0.009$). Experience pilots seem to be more cautious since their response time is significantly longer than novice pilot when movement is slow and medium and time delay is long.

Chapter 7 General Discussion and Recommendation

7.1 Distance Estimation

For the first step, participants estimated the current location of a storm based on the amount of time delay and the storm's movement speed. The static radar image and animation provided the direction and the movement speed of storm cells. If participants did not have the ability to estimate the current location of the storm or were not sensitive to the movement speed and amount of time delay, the difference of estimation was insignificant among factors levels. Participants overestimated the current location when the time delay was short or medium and the storm had slow and medium movement speed. Participants underestimated the current location when the movement was fast and time delay was long.

For the second step, participants estimated the current distance between the storm cell and the aircraft based on the current location. The study indicated that participants did not account for the movement speed and the amount of time delay into the distance estimation, so the estimation purely estimated the distance between two points. However, based on the model of information integration and situation awareness, the time delay and movement speed would definitely affect the current distance estimation. Participants tended to underestimate the current distance. Accuracy estimation was the highest when the movement speed is slow or fast and time delay was long. Estimates of the current distance were least accurate when the storm had a medium speed and medium time delay.

For the third step, participants estimated the future distance between storm cells and aircraft based on the step one and two. Participants underestimated the distance when movement was slow or medium and time delay was short. However, participants overestimated the distance when the movement was fast and time delay was medium or long. Future distance estimations were least accurate when the storm had slow movement and short time delay. From this point, long time delay and fast movement was easy for participants to estimate and had a high accuracy.

In the third step, participants overestimated the future distance when movement was fast and time delay is long. At the same time, the accuracy was much higher than the estimation when the movement was slow and time delay was short. So participants tended to be very cautious when dealing with the fast movement and long delay and they have the ability to perform the estimation. The estimation trend seemed to make the range of future distance "expand" (overestimation when fast movement and long delay; underestimation when slow movement and short delay).

Wickens (2002) reported that if pilots were unsure of the location of a weather hazard on the display, because of resolution, scale, or other factors, the pilots may choose to behave on the "safe side" and be very conservative. That is, a pilot will choose to fly farther away from the hazard. In this study, participants' estimation tended to be conservative in the three steps (see Table 7.1). Sometimes pilots think the weather condition is better than the real condition (Coyne, Baldwin &Latorella, 2008).

Wickens (2002) also noted that the integration of multiple sources of information will be difficult by involving complex computation, mental arithmetic, and spatial arithmetic. Estimating a total distance involves addition; subtraction is involved into estimating distance remaining to a storm cell; multiplication is involved in the estimating the distance to be traveled from a speed and time. Addition is easier than subtraction which is easier than multiplication. In this study, it was certainly true that spatial arithmetic was involved in the three steps (see Table 7.1).

Table 7.1 The summary of the three steps

	Step 1: current location estimation	**Step 2: Current distance estimation**	**Step 3: future distance estimation**
Range of original distance	5--20nm	10--70nm	10-70nm
Information Integration	Scale, timestamp, movement speed	Scale, range ring, own-ship	Scale, range ring, speed
Spatial Arithmetic	Multiplication	Addition	Subtraction
Higher Accuracy	Slow and medium Short and medium	Slow and fast long	Fast Long and medium
Estimation Error	overestimate	underestimate	overestimate
SA stages	Stage two	Stage two	Stage three

Wickens (2002) reported that the difficulty inherent in the spatial arithmetic operations influenced the extent of distance estimation and the extent that displays can help estimation and reduced the computational load of the integration. In this study, spatial arithmetic affected the distance estimation in each step and the level of difficulty was likely similar for addition and subtraction.

In step two and three, participants' distance estimation mainly relied on the afterimage of the mental representation of storm movement since the animation stopped and couldn't be replayed again. Participant had to be very cautious and conservative so that they could avoid the storm cell, which potentially resulted in the higher accuracy for long time delay and fast movement.

7.2 Types of Display

In this study, there was no significant difference of distance estimation between two types of display, which was consistent with previous research (Bergess & Thomas, 2001). However, the interaction effect of display type with movement and time delay was significant in three steps. In the step one, two types of display directly affected the distance estimation. Results showed that participants would overestimate the distance using a static image while underestimate using an animation. The animation display provided direct and intuitive movement and spatial cues. Static images provided speed and direction directly. If participants knew the time, participants could mentally compute the distance. When the time delay was long and movement is slow or medium, accuracy of estimation using animation is lower comparison to use of the static image. Participants may be more capable of mental computations when storm movement was slow or medium and illustrated with a long delay. Under other conditions, participants may not easily mark the current location of storm.

The results of the questionnaire showed that participants preferred animation over static images. The speed vector on the static images helped participants compute precise distance. Therefore, when there is a long time delay and animation is difficult to use, static images are a good option. The combination of animation and speed vectors could provide a helpful visual aid for distance estimation tasks.

7.3 Weather Situation Awareness

Weather situation awareness of pilots is well represented by the three steps of the distance estimation (Endsley et al., 1998; Latorella & Chamberlin, 2002). In the first experiment, "direct age" timestamp supported time awareness by directly providing participants with a known amount of time delay. Participants' projection of the distance between the storm and aircraft was another aspect of the time awareness. The spatial awareness was measured through the current location and distance estimation. Those design features on the display, such as range ring, scale, and own-ship supported the spatial awareness.

Novice and experience pilots demonstrated different ability for integrating those design features and projecting future situation (Shook, et al., 2000). Because inexperienced pilots had more difficulty in projecting future situations, they required more training to develop this spatial awareness and skills. In this study, experienced pilots seemed to be more cautious and conservative than novice participants.

The measurement of SA in this study used the performance measure method, which obtained objective data to measure how well participants processed the delayed radar information. Since the accuracy is high when movement is fast and time delay is long in the step three, participants may make tactical judgment using data that were delayed up to 20-minutes time delay. Participants reported that greater time delay resulted in less certainty and more conservative decisions. Providing the exact and precise time delay and project path helped participant to trust and use the delayed radar information.

Using SART as the post questionnaire, results showed that there is no significant difference between the novice and experienced participants and between the two types of display. In the experiment, all the stimuli were randomly shown and participants completed a lot of mental computation. After completing the experiment, participants may not have remembered how they completed the computation in each step with the different levels of factors. So their answer to each question is very neutral.

7.4 Limitations of This Study

Although the experiments were designed to use real weather scenarios, all of the stimuli were made up and the tasks of the participants were separated into three sub-tasks. The contrast between the symbols and the background images were not very significant so future studies should increase the contrast of these features.

In addition, the distance estimation method was not very objective or precise. The point marked on the image with an X would disappear with movement actually; however, it was assumed to be continuously displayed so that participants could see it. When participants estimated the distance, they may introduce some subjectivity and inaccuracy.

Distance deviation was used as the independent variable instead of the angle since the angle biases were very small and the angle was not discernible from the data. In the future, the angle distribution could be investigated and may provide some useful insights.

7.5 Contributions

In the model of SA, developed by Endsley (1995), the SA is separated from the information processing mechanism. The definition of SA was based on the information processing and state of the dynamic environment during a coincident storm event and flight path. In this study, we combined the SA into the information integration theory so that SA and information processing mechanism became a whole model. The information processing mechanism is designed to integrate all of the information to support different stages of SA.

SA was also separated into three phases based on the time dimension of information: past, current, and future situations. Because of the differences in conditions, various designs could be used to support the three phases. In the past phase, timestamp was used to help pilots know the exact time delay and to attach great importance to the time delay. In the second phase, good scale, range ring and animation with a speed vector were displayed on the radar information. In the third phase, projected track path was recommended to the participants. The extent of pilots training may be related to their ability to use delayed information to make tactical decisions.

Pilots in the cockpit of an aircraft use delayed radar information to project future condition. The public also commonly use delayed weather information issued by the media for decision making. Further study of decision making by pilots when using delayed information may provide insights into decision making by the general public in severe weather events such as tornados or hurricanes.

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Appendix. Questionnaires

Demographic questionnaire

Subject No.________

First Name_________

Date ___________

1. Gender: Male Female

2. Age: _______

3. For what categories of aircraft do you hold a certificate(s)? (Please check **all** that apply)
   Airplane Rotorcraft Glider Lighter-than-air

4. What certificate (s)/rating (s) do you currently hold? (Please check **all** that apply)
   Student Pilot Recreational Pilot Private Pilot Instrument Commercial
   ATP CFI CFII MEI SEL MEL SES MES A & P

5. How many total hours of flying do you currently have? ___________________ hours

6. How many hours have you flown in the past six (6) months? _______________hours

7. When did you pass your check ride/practical test for your most recently obtained a certificate / rating? __________________ month/year

8. What is your most recently obtained certificate/rating? ______________________

Weather Knowledge Survey

We would like to learn a little more about your aviation weather knowledge before you participate in our study. Please take a couple of minutes to answer a few questions. Your answers are strictly confidential and will not be released.

1. You are scheduled to be at another airport that is 120 miles to the north. A thunderstorm is 50 miles away from your destination airport and is approaching it at 25

knots from the northwest. It is also growing in size and intensity. You plan to fly at 120 knots. You decide to:

(a) Takeoff and circle around the thunderstorm and approach your airport behind it.

(b) Wait with the airplane until the weather passes, then fly into your next airport.

(c) Fly the airplane anywhere away from the path of the storm

(d) Leave the airplane and wait out the storm.

2. What does a narrow temperature/dewpoint spread mean? ________________

3. How many nautical miles away from the storm is safe for aircraft_____________

4. Please list three stages(life cycle) of thunderstorm?

____

5. What COMM frequency can you use to contact Flight Watch? _______________

6. How much does 20 gallons of 100 LL fuel weigh? ________________________

7. If you are flying eastbound, and you have a tailwind, would you typically be north or south of a low pressure zone?

____

8. On a surface analysis weather chart, what do closely spaced isobars mean?

____

9. In what weather products can you find icing information?

____

10. What do boundary layer air, and surface winds near the ground have in common?

____

11. If a thunderstorm is identified as being severe, or giving an intense radar echo, what does the AIM say about how far you should avoid the storm?

12. On a radar summary chart, what does the notation "NA" mean?_____________

13. On the radar image, how much DBZ is in the red area(range).___________

14. What does the symbol  means in avionic meteorology?_____________

15. What is Zulu time?____________________________________

Post-test Questionnaire

1. Have you ever used a data linked in-flight weather display system in a flight? (not including onboard radar or Storm scope)

    (Yes/No)

    If yes, how many flights hours do you have with it? _________________

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

    ____

3. How useful was the static display?

    1---no useful at all 2---no useful 3---neutral 4--- useful 5--- very useful

4. How useful was the dynamic display?

    1---no useful at all 2---no useful 3---neutral 4--- useful 5--- very useful

5. What information did you use information available to you when formulating the distance judgment? ______________________

6. For you to formulate the distance judgment for current time, how useful was the speed vector?

    1---no useful at all 2---no useful 3---neutral 4--- useful 5--- very useful

7. How useful was the display of time stamp?

   1---no useful at all 2---no useful 3---neutral 4--- useful 5--- very useful

8. What information did you use to estimate distance with static display______

9. What information did you use to estimate distance with the animation display?

   ____

10. How difficult was it for you to estimate current distance according to the animation display?

    1---very easy 2--- easy 3--- neutral 4---difficult 5---very difficult

11. How difficult was it for you to estimate current distance according to the speed vector in static display?

    1---very easy 2--- easy 3--- neutral 4---difficult 5---very difficult

12. How difficult was it for you to estimate distance 15 minutes into the future according to the animation display?

    1---very easy 2--- easy 3--- neutral 4---difficult 5---very difficult

13. How difficult was it for you to estimate distance 15 minutes into the future according to the speed vector in static display?

    1---very easy 2--- easy 3--- neutral 4---difficult 5---very difficult

When Viewing the Static Images

1. How changeable is the situation?
   Is the situation highly unstable and likely to change suddenly (High) or is it very stable and straightforward (Low)?
   1-----2----3----4----5---6---7

   Low High

2. How complicated is the situation?

Is it complex with many interrelated components (High) or is it simple and straightforward (Low)?

1-----2----3----4----5---6---7

Low High

3. How many variables are changing within the situation?

Are there a large number of factors varying (High) or focused on only one (Low)?

1-----2----3----4----5---6---7

Low High

4. How aroused are you in the situation?

Are you alert and ready for activity (High) or do you have a low degree of alertness (Low)?

1-----2----3----4----5---6---7

Low High

5. How much are you concentrating on the situation?

Are you concentrating on many aspects of the situation (High) or focused on only one (Low)?

1-----2----3----4----5---6---7

Low High

6. How much of your attention is divided in the situation?

Are you concentrating on many aspects of the situation (High) or focused on only one (Low)?

1-----2----3----4----5---6---7

Low High

7. How much metal Capacity do you have to spare in the situation?

Do you have sufficient to attend to many variables (High) or nothing to spare at all (Low)?

1-----2----3----4----5---6---7

Low High

8. How much information have you gained about the situation?

Have you received and understood a great deal of knowledge (High) or very little (Low)?

1-----2----3----4----5---6---7

Low High

9. How familiar are you with the situation?

Do you have a great deal of relevant experience (High) or is it a new situation (Low)?

1-----2----3----4----5---6---7

Low High

When Viewing the Animation Images

1. How changeable is the situation?
   Is the situation highly unstable and likely to change suddenly (High) or is it very stable and straightforward (Low)?
   1-----2----3----4----5---6---7

   Low High
2. How complicated is the situation?
   Is it complex with many interrelated components (High) or is it simple and straightforward (Low)?
   1-----2----3----4----5---6---7

   Low High
3. How many variables are changing within the situation?
   Are there a large number of factors varying (High) or focused on only one (Low)?
   1-----2----3----4----5---6---7

   Low High
4. How aroused are you in the situation?
   Are you alert and ready for activity (High) or do you have a low degree of alertness (Low)?
   1-----2----3----4----5---6---7

   Low High
5. How much are you concentrating on the situation?
   Are you concentrating on many aspects of the situation (High) or focused on only one (Low)?
   1-----2----3----4----5---6---7

   Low High
6. How much of your attention is divided in the situation?
   Are you concentrating on many aspects of the situation (High) or focused on only one (Low)?
   1-----2----3----4----5---6---7

   Low High
7. How much metal Capacity do you have to spare in the situation?
   Do you have sufficient to attend to many variables (High) or nothing to spare at all (Low)?
   1-----2----3----4----5---6---7

   Low High

8. How much information have you gained about the situation?

   Have you received and understood a great deal of knowledge (High) or very little (Low)?

   1-----2----3----4----5---6---7

   Low High

9. How familiar are you with the situation?

   Do you have a great deal of relevant experience (High) or is it a new situation (Low)?

   1-----2----3----4----5---6---7

   Low High

Interview Questions:

Please describe your strategy to figure out current distance with static display.

Please describe your strategy to figure out current distance with animation display.

Are your strategies same when you try to figure out distance 15 minutes into the future.

Would you notice the time delay of a weather display if not explicitly instructed to pay attention to it?

How would you redesign the static display to make your task easier?

How would you redesign the animation display to make your task easier?

Do you think that you could develop a rule, based on your experience, which could assist another person to make the same judgment successfully? (Y/N)_____

If yes, what is the rule? ____

Based on your experience, how does the amount of time delay in weather display affect you when you fly?