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Designing a Flight Deck Predictive Weather Forecast Interface Supporting Trajectory-Based Operations

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***Abstract*—It is envisioned in NextGen that predictive weather forecasts will be available and assimilated into decision making processes. There however has been limited discussion on how weather avoidance decisions based on predictive forecasts are to be made and executed on the flight deck under Trajectory-Based Operations (TBO). The present study examined three prototype methods by which predictive weather forecasts can be viewed in conjunction with tools to modify flight trajectories. Eighteen transport pilots participated in a part-task experiment where they were asked to modify flight trajectories when necessary using one of the three methods. Subjective evaluations by the pilots showed overall acceptance of the concepts behind all of the methods, with room for improvement in the implementation of each. Performance results showed that different methods were preferable under different weather encounter scenarios. Implications on designing interfaces to support weather decisions in Air Traffic Management (ATM) environments will be discussed.**

Keywords-predictive weather; flight deck; trajectory-based operations; eyetracking; part-task; human factors

I. Introduction

One of the main objectives of the Next Generation Air Transportation System (NextGen) is to expand the capacity of the U.S. National Airspace System (NAS) in order to meet the anticipated growth in traffic demand and operation diversity. This objective is to be met on the one hand by having aircraft engage in trajectory-based operations (TBOs) in order to reduce transit time and increase predictability; and on the other hand by assimilating observed weather information and probabilistic forecasts into the decision making process of flight crews and air traffic controllers in order to minimize weather impact [1]. There has been limited discussion on how weather avoidance decisions are to be made and executed in the context of performing TBO, much less what flight deck interfaces are needed to support both operations.

The present research represents an initial effort in pursuit of a flight deck interface design that supports the display of predictive weather forecasts used in conjunction with tools that enable in-flight trajectory planning. Specifically, we examined three plausible methods for displaying predictive weather forecasts and tested their usability in a part-task experiment. We begin the paper by reviewing technological developments focused on representing probabilistic weather forecasts, followed by a discussion of the philosophy behind the specific types of display interfaces we have chosen to empirically examine. We then describe the three methods in detail, and how we examined them in the part-task experiment. Finally we report the results from the study and discuss their implications for supporting weather decisions by pilots on the flight deck as well as by air traffic controllers on the ground.

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A. *Displaying Predictive Weather Forecasts*

Predictive weather forecasts, particularly convective forecasts, have mainly been designed for, and made available to, air traffic controllers and airline dispatchers on the ground for tactical and strategic planning purposes. For example, the Collaborative Convective Forecast Product (CCFP) is the primary tool brought together by the meteorological community and the commercial aviation industry to address the impact of convective weather on the NAS at strategic time frames of 2-6 hours [2]. The CCFP has been undergoing continual revisions since it was first brought out in 1999 in terms of its update cycle and geographical coverage, as well as its graphic representations [3]. In its current version, the CCFP is available primarily in an ASCII coded text format [4]. There are also simplified graphical representations of part of the information. Early versions of the CCFP painted color coded polygons over a map of the domestic US to represent convective activities [5]. Colors in yellow, orange, and red represents expected coverage from low (25% to 49%) to high (75% to 100%). Polygons are accompanied by a textbox providing additional information including echo tops and confidence levels. The current version of CCFP uses the density of pattern shading (sparse, medium, and solid) to represent coverage and uses color (gray and blue) to represent the forecaster's confidence level (low and high, respectively).

B. *Design of a Flight Deck Predictive Weather Display for TBO*

Being on different sides of the same team, controllers and pilots have different needs for predictive weather forecast information. Controllers are concerned with the impact of hazardous weather on a larger scale, particularly how route blockage by weather is going to alter traffic flow and reduce airspace capacity. Pilots, however, are concerned with the impact of hazardous weather on a smaller, local scale, specifically whether their flight's trajectory determined before departure can still be followed, and if not, how it should be modified. The unique challenge for a flight deck predictive weather interface that also supports TBO is that it needs to be capable of allowing pilots to translate weather avoidance decisions into flight plan changes and to implement these changes and communicate them to the controller.

Most would agree that the conventional pilot-aircraft interface in use today, the Flight Management System (FMS), is far from meeting that challenge. On modern flight decks, pilots interact with the FMS through the Control Display Unit (CDU), which has a text-based display and utilizes an alphanumeric input method. Simply communicating a flight trajectory in tracks and navigation aids to the controller has already been shown to be difficult for a flight deck not equipped with an advanced data communication system such as FANS-1A [6], not to mention the foreseeable difficulty in planning and constructing 4D trajectories to go around weather while conforming to TBO imposed constraints.

Clearly, the inherently spatiotemporal nature of navigation and trajectory planning could benefit greatly from having a direct manipulation interface for manipulating the display of predictive weather forecasts and at the same time supporting graphical in-flight trajectory planning. The idea of direct manipulation interfaces come from the principles behind ecological interface design (EID), advocated by Rasmussen and Vicente in the late 1990s [7-10] It is postulated that an operator uses an interface to interact with a system at three cognitive levels: skill-based, rule-based, and knowledge-based. The skill-based level describes the level at which the operator acts using the provided methods to send commands and cause state changes. The rule-based level describes the level at which the operator uses cues or feedback provided by the interface to determine what actions to take at the skill-based level. The knowledge-based level describes the level at which the operator conducts abstract reasoning to form a mental model of the system behind the interface in order to interpret the cues and feedback. The principle idea behind EID is to design an interface such that whatever an operator needs to accomplish at each of the three levels is directly supported by the interface itself.

For example, take a task such as examining predictive weather forecasts for weather avoidance. The kind of information that pilots want to learn from examining the forecasts is where, throughout an upcoming interval of time, their aircraft will be relative to where the storms are expected to be; and whether their aircraft may come close to the storms at any point in that time interval. Text-based forecast data, such as that provided by the CCFP, could not be readily translated by pilots into information that allows them to envision the future. The kind of support pilots might desire in such a situation is a way to dynamically display both predicted aircraft movement and weather development in a 3D space, and thus be able to visualize future conditions. As such, the knowledge-based level of processing demanded by the interface would match that of the pilot's operational environment, the surrounding airspace. Furthermore, if pilots could see their aircraft represented in the interface and were able to control its spatiotemporal trajectory, just as they do when flying through the airspace, the interface would support the skill-based and rule-based levels directly. Mulder and colleagues [11] describe an attempt to design a direct manipulation interface for 4D in-flight re-planning. They found that, when provided with a moderate amount of detail, pilot performance benefits greatly from such an interface design.

In the next section, we describe our version of a direct manipulation interface that supports in-flight 4D trajectory planning and the viewing of predictive weather forecasts.

II. FLIGHT DECK WEATHER DECISION INTERFACES

A. Cockpit Situation Display (CSD) and the Route Assessment Tool (RAT)

The Cockpit Situation Display (CSD), an extension of a Cockpit Display of Traffic Information (CDTI), is an interactive display prototype that has been in development in the Flight Deck Display Research Laboratory at NASA Ames Research Center for over a decade (Fig. 1). The CSD supports both traditional 2D and advanced 3D visualization models, and depicts the 4D interrelationship of traffic, terrain, and weather using a cylindrical volume metaphor. Designed to provide the basis for 4D TBO, the CSD also includes the Route Assessment Tool (RAT) which is integrated with the aircraft's Flight Management System (FMS), and allows for in-flight trajectory replanning. A standard computer mouse is presently used to interact with the CSD prototype.

The RAT adopts the principle of a direct manipulation interface providing the functionality to create and visualize in-flight route modifications, downlink proposed route modifications to Air Traffic Control (ATC), receive route

Figure 1. A screenshot of the CSD

modifications from ATC, and execute modifications. The RAT supports the addition of waypoints at arbitrary latitudes-longitudes, and deletion of waypoints, through both clicking and dragging-and-dropping mouse operations. For each waypoint, pilots can also adjust an associated flight altitude and speed, thus enabling 4D trajectory in-flight planning.

B. Three Methods for Displaying Predictive Weather Forecasts

All three methods for displaying predictive weather can be used for simple monitoring, or in conjunction with the RAT, for route planning. The visual depictions of the current and predicted weather are the same under all three methods. Specifically, current weather is depicted in layers of green yellow, and red, resembling the intensity classification used in radar weather images. Predictive weather forecasts are displayed in a semi-transparent gray color in order to be distinct from the current weather depiction. The three methods differ primarily in the way the predictive range (how far into the future the prediction goes) is specified and the interface used to adjust it.

In the first method, henceforth referred to as the *Pulse* method, the predictive range is set by clicking the Pulse button on the CSD toolbar that specifies the prediction interval. This predictive interval is incremented in steps of 1 minutes by a right mouse button click, and decreased in the same steps by a left mouse button click. What is unique about the Pulse method is that, when it is selected, and the predictive interval set, a corresponding dynamic synchronous extrapolation of the predicted weather (in gray) and aircraft position (drawn as a blue bead) *over the length of the specified time interval into the future* is repeatedly shown on the display. Thus, if at time *t* a pilot engaged the Pulse method, and selected a predictive interval of 6 minutes, he or she would initially see a repeating fast-time prediction going from time *t* to time *t+6*. If the pilot left the Pulse method engaged, the starting point (i.e., the aircraft) would continually move forward such that (for example), at time *t+1* the pilot would be seeing a fast-time prediction going from *t+1* to *t+7*.

In the second method, henceforth referred to as the *Slider* method, the predictive range is set by a prediction interval-based slider located at the lower left of the CSD display. When the pilot uses the mouse to drag the slider to select different time intervals, the blue bead indicating the projected aircraft position and the weather forecasts will accordingly update to reflect predicted aircraft position and weather forecast at the specified time interval into the future. The Slider method provides the pilot a method to select and hold in focus aircraft and weather position *at the end of a specific time interval into the future*. So, in contrast to the *Pulse* example used above, the pilot would start off at time *t* seeing only the weather forecast for time *t+6*, and at *t+1* only seeing the forecast for time *t+7*.

In the third and final method, henceforth referred to as the *Route* method, the predictive range is adjusted by directly manipulating the spatial position of the blue bead along the future planned route of the aircraft. When the pilot moves the bead to a spatial position on his or her existing or proposed trajectory, the time at which the aircraft is expected to reach this point is calculated, and the weather forecast corresponding to this time is then displayed. The main contrast between the Route method, as opposed to the Pulse or Slider methods, is that the Route method is associated with a location, while the other two methods are associated with a time. For example, if a location along the route is selected in the Route mode, a predicted time would initially be ascribed to that location. But as the aircraft progressed, the predicted time will continuously count down until the pilot changes the location or turns off the prediction.

III. EXPERIMENT

The present research consisted of a part-task experiment evaluating three plausible methods for presenting weather forecasts with tools that support trajectory planning. The experiment focused on evaluating the usability of the methods for supporting the viewing of predictive weather forecasts for weather avoidance decisions. To simplify matters, only a single aircraft (ownship) was present in the scenarios, and the trials terminated upon completing the route modification. Traffic was not a consideration in this experiment, and perfect predictions were assumed.

A. Participants

Twenty-one transport pilots with 1000 to over 5000 hours of high-altitude flight experience participated in the study and were compensated $25/hr. Among them, 18 pilots had experience using the CSD in previous studies in the lab, but none had experience with the weather prediction tools.

B. Apparatus

The study was conducted using an IBM-compatible desktop personal computer (PC) equipped with a 30” LCD display. Pilots manipulated the CSD using a computer mouse. Eye movements were monitored using a head-mounted camera-based eyetracking system (Applied Science Laboratory, Model 501). The system samples eye position at 120 Hz.

C. Design

On each trial, pilots were presented with a weather encounter scenario in en route environments and asked to modify the existing trajectory if they found it unsafe according to predictive weather forecasts. In addition to the three methods for viewing predictive weather forecasts, we manipulated the distance of the current ownship to the location on the initial trajectory where ownship was expected to reach the closest point of approach (CPA) to weather. These distances could be either 40 nm (~5 min) or 80 nm (~10 min). At either of the distances, ownship could encounter hazardous weather in one of four ways:

- Middle: On these trials, the existing 3D ownship trajectory, and the 4D forecast ownship trajectory, penetrated one of the storm cells near the center of a storm front. It was designed such that it would be very inefficient to take a large detour and bypass all of the storm cells so that pilots would be more tempted to find an alternative route through the gaps between storm cells.

- Initially clearing gap: On these trials, the existing 3D ownship trajectory was initially clear of the given line of storm cells, passing through a gap in the current weather depiction. However the forecast 4D trajectory was predicted to penetrate the storm cells.
- Initially clearing edge: On these trials, the existing 3D ownship trajectory appeared to clear the leading or trailing edge of a line of storm cells in current weather depictions, but the forecast 4D trajectory was predicted to penetrate the storm cells.
- Clear later: On these trials, the existing 3D ownship trajectory penetrated storm cells in current weather depictions, but the forecast 4D trajectory was predicted to be clear of weather.

Trial scenarios were generated using three types of weather patterns in order to increase the variability of the scenarios. A total of 144 unique trial scenarios were generated, with 48 trials in each of the predictive weather viewing conditions. The 48 trials varied according to the three weather patterns, four encounter types and two distances.

D. Procedure

Each trial began with a crosshair fixed at the center of a blank CSD display. After a variable amount of time, between 2-4 seconds,[1] the trial display appeared with ownship in the center. The display range was set to 320 nm (160 nm in front and behind ownship), with the trajectory extending upward ahead of ownship to the edge of the display. Storm cells were located at variable distances ahead of ownship in the upper half of the display. Pilots were asked to determine if a given flight trajectory was safe and, if the trajectory was determined to be unsafe, find a safe and efficient re-route around weather using the shortest amount of time. They were instructed to use their company's standard operation procedure (SOP) for avoiding hazardous weather. Each trial ended when the pilot executed the modified flight trajectory using the RAT. On trials where pilots determined that no modification was necessary, they activated the RAT and executed the existing trajectory to terminate the trial. Following the end of a trial, a dialog box appeared in the center of the display with an OK button. As soon as the pilot clicked the OK button, the next trial began.

The 144 trials were divided into three blocks, one for each weather viewing method. The order of the blocks was counterbalanced between pilots. Pilots received the corresponding training for a particular method right before that block of trials. The training involved verbal instructions and hands-on exercises, followed by self-paced practice runs. Pilots were asked to practice until they felt comfortable using the newly learned method. Before testing began in each block, pilots went through an eyetracker calibration procedure to ensure accurate recordings. After pilots completed all blocks of trials, they filled out an online questionnaire designed to solicit their subjective evaluation of the three viewing methods.

On all trials the altitude of ownship was preset to 33000 feet; and the speed was preset to around 464 knots. Because it was assumed that the type of weather avoidance being studied here takes place en route, pilots were instructed to view the display in 2D and perform only lateral maneuvers even though CSD and RAT support 3D operations. No wind information was provided; pilots were instructed to infer wind direction based on the forecasted movement of the storm cells. The experiment provided up to 40 minutes of weather forecasts. The prediction was assumed to be 100% accurate.

IV. RESULTS

Three of the 21 pilots were excluded: one due to excessive conversation during testing, two others due to poor tracking quality. Results reported here are based on the remaining 18 pilots, who together fulfilled a complete counterbalancing of the three viewing method orders.

A. Performance Results

The primary criterion for a good predictive weather viewing interface for the flight deck should be how well they support the generation of alternative safe flight trajectories around hazardous weather. To that end, we examined the time taken to generate route modifications and their quality. In the current study, the typical work flow on a trial involves first using the provided predictive weather viewing method to determine whether a route modification is necessary, and when needed, generating an alternative safe trajectory around weather using the RAT. Therefore, there is a period of time where predictive viewing methods are used primarily for weather evaluation independent of route modification, and another period of time when the viewing methods are used in conjunction with route modification. We measured the evaluation time from when ownship and weather were shown to when the RAT was first activated, and modification time from when the RAT was first activated to when a route (new or existing) was executed. Because some pilots adopted the strategy of activating the RAT without having evaluated the predictive weather forecasts first, we also took the sum of the evaluation and modification time as a measure of weather avoidance efficiency in general.

The results of averaged evaluation time, modification time, and total time by viewing methods, distance to weather, and weather encounter type are summarized in Tables 1-3. The results were subjected to repeated-measure Analyses of Variance (ANOVA) with within-subject factors of viewing method (Pulse, Slider, and Route), distance to weather (40 and 80 nm), and encounter type (Middle, Initially clearing gap, Initially clearing edge, and Clear later). With regard to evaluation time, there were significant main effects of distance, $F(1,17) = 19.22$, $p < .0005$, and encounter type, $F(3,51) = 11.26$, $p < .0005$. Specifically, when the distance to encounter weather on the existing trajectory was close (40 nm), pilots spent less time evaluating weather and proceeded quickly to modify the existing trajectory using the RAT (10.0 sec at 40 nm vs 10.8 sec at 80 nm). Pilots also spent relatively a longer time evaluating weather conditions prior to activating the RAT

[1] The variable delay was the time taken by the hardware and software to render and present the weather cell objects in 3D.

TABLE 1. MEAN EVALUATION TIME (SEC) IN THE THREE VIEWING CONDITIONS BY DISTANCE AND ENCOUNTER

Viewing Method	Encounter Type			
	Middle	*Initially clearing gap*	*Initially clearing edge*	*Clear later*
Pulse				
40 nm	11.3	10.6	9.2	10.1
80 nm	11.7	11.9	9.6	11.3
Slider				
40 nm	11.2	10.0	7.9	9.0
80 nm	10.6	10.3	9.2	9.9
Route				
40 nm	11.0	10.5	9.4	10.0
80 nm	11.7	11.8	10.1	11.3

TABLE 2. MEAN MODIFICATION TIME (SEC) IN THE THREE VIEWING CONDITIONS BY DISTANCE AND ENCOUNTER TYPE

Viewing Method	Encounter Type			
	Middle	*Initially clearing gap*	*Initially clearing edge*	*Clear later*
Pulse				
40 nm	24.9	19.8	14.7	12.7
80 nm	23.6	23.5	14.2	13.9
Slider				
40 nm	26.2	21.9	16.2	12.2
80 nm	23.9	22.2	14.7	11.9
Route				
40 nm	23.5	19.0	15.5	12.0
80 nm	21.8	20.0	13.7	13.1

TABLE 3. MEAN TOTAL TRIAL TIME (SEC) IN THE THREE VIEWING CONDITIONS BY DISTANCE AND ENCOUNTER TYPE

Viewing Method	Encounter Type			
	Middle	*Initially clearing gap*	*Initially clearing edge*	*Clear later*
Pulse				
40 nm	36.1	30.4	24.0	22.8
80 nm	35.4	35.4	23.8	25.2
Slider				
40 nm	37.4	31.9	24.1	21.2
80 nm	34.5	32.5	23.9	21.8
Route				
40 nm	34.6	29.5	24.8	22.0
80 nm	33.5	31.7	23.7	24.4

when the given trajectory went through the middle of a line of storms (11.3 sec on average), whereas they spent relatively less time when the given trajectory initially cleared the edge of the line of storm cells (9.2 sec on average). There was no significant effect of the viewing method.

The ANOVA results on route modification time showed a slightly different pattern to those on evaluation time. There was again a main effect of encounter type, $F(3,51) = 41.48$, $p < .0005$. It appeared that pilots took longer to generate alternative safe trajectories around weather when the initial trajectory went through the middle of a line of storm cells (around 22.5 sec on average) than when the initial trajectory cleared the outer edge of storms or would entirely clear them as the aircraft approached (around 13.7 sec on average). The effect of distance to weather came in the form of an interaction with encounter type, $F(3,51) = 3.71$, $p < .05$; trajectory modifications were easier with different encounter types depending on the distance to weather in a way that was not readily interpretable. There was again no effect of the viewing method other than a marginal interaction with encounter type, $F(6,102) = 1.92$, $p = .08$, again in a pattern not readily interpretable.

The ANOVA results on the total weather avoidance time (evaluation plus modification time) again showed a significant main effect of encounter type, $F(3,51) = 40.56$, $p < .0005$, as well as an interaction between distance and encounter type, $F(3,51) = 4.41$, $p < .05$. It appears that, short time horizons made it more difficult to evaluate and modify a trajectory initially going through the middle of a storm cell but made it easier to handle a trajectory initially going through the gap between cells. There was a significant interaction between viewing method and encounter type, $F(6,102) = 2.31$, $p < .05$. It is somewhat difficult to characterize this interaction other than to note a small tendency for the Route method to produce relatively faster route evaluation and modification time when the encounter type required more difficult maneuvers (e.g., middle and initially clearing gap).

The quality of route modification was evaluated in terms of the increase in length of the modified path compared to the

TABLE 4. MEAN PATH STRETCH (NM) IN THE THREE VIEWING CONDITIONS BY DISTANCE AND ENCOUNTER TYPE

Viewing Method	Encounter Type			
	Middle	*Initially clearing gap*	*Initially clearing edge*	*Clear later*
Pulse				
40 nm	35.0	19.7	7.0	14.3
80 nm	24.1	26.0	6.3	11.9
Slider				
40 nm	25.8	22.6	5.8	9.7
80 nm	34.9	29.1	5.6	11.7
Route				
40 nm	30.4	17.5	5.4	9.0
80 nm	22.5	22.7	5.4	12.5

original one and the new path's proximity to weather. It is assumed that a good predictive weather viewing interface would make it easier to find the shortest reroute around weather at a safe margin. The ANOVA results on path stretch (summarized in Table 4) showed a significant main effect of encounter type, $F(3,51) = 13.95$, $p < .005$, and an interaction between distance to weather and encounter type, $F(3,51) = 4.72$, $p < .05$. As anticipated, a flight trajectory that starts out clearing the edge of a line of storm cells required the least amount of modification to be clear of the storm cells (5.9 nm on average), whereas an initial trajectory penetrating a line of storm cells may prompt a pilot to make large detours to avoid them altogether, resulting in the greatest increase in path length (28.8 nm on average). What is interesting though, as revealed by the interaction between distance to weather and encounter type, is that when weather encounter was imminent (40 nm to CPA to weather), pilots made shorter route modifications than when the weather encounter was much further away, particularly in the condition where the initial trajectory started out being clear of weather (i.e., Initial clearing gap). In general, the increase in overall path length required to avoid weather grows as you approach it more closely. Therefore it may be that pilots were more willing to trade off risk for efficiency when the safer path was very inefficient. Alternatively, the pilots may have been willing to take a little more risk to fly between cells when the time to find and execute a new path was more limited (5 min versus 10 min).

The ANOVA results on the new path's proximity to weather support the above conjecture. These results (summarized in Table 5) showed main effects of distance to weather, $F(1,17) = 16.25$, $p < .001$, and encounter type, $F(3,51) = 162.39$, $p < .0001$, as well as an interaction between distance to weather and encounter type, $F(3,51) = 90.61$, $p < .0001$. When ownship was closer to encountering hazardous weather, the modified paths tended to maintain a smaller safety margin. The degree to which pilots were able to maintain the safety margin under the FAA guidance (20 nm) appeared to be closely related to how easy it was to plan an alternative safe trajectory, as indicated by the effect of encounter type. Only when the initial trajectory was already clearing the edge of a line of storm cells did the pilots maintain a safety distance (19.5 nm) close to the FAA guidance. In all other encounter situations, the average safety margin was well below the guidance, especially when the initial trajectory penetrated the line of storm cells in the middle and greatly increased the difficulty in maneuvering.

B. Subjective Evaluation Results

Pilots rated the methods in terms of their ease of use in accomplishing various tasks (5-point Likert scale, from very difficult to use to very easy to use) and potential utility in various situations not represented in the experiment (5-point Likert scale, from useless to have to very useful to have). Table 6 summarizes the distribution of pilots giving out a particular rating for the implementation and utility of the three methods. Results of a repeated measure of ANOVA on the averaged implementation ratings showed a significant effect of method, $F(3,24) = 3.28$, $p = .05$. A separate ANOVA on the utility rating showed a significant effect of method, $F(2,34) = 4.78$, $p < .05$. The Pulse method received the highest ratings in terms of both implementation and utility, followed by the Slider method and lastly Route method. Despite the statistical differences, all methods were rated highly (i.e., between somewhat easy to use/useful to have to very easy to use/useful to have) for their implementation and potential utility, except the Route method which had an averaged utility rating slightly under 4 (i.e, somewhat useful to have).

TABLE 5. CPA TO WEATHER (NM) IN THE THREE VIEWING CONDITIONS BY DISTANCE AND ENCOUNTER TYPE

Viewing Method	**Encounter Type**			
	Middle	***Initially clearing gap***	***Initially clearing edge***	***Clear later***
Pulse				
40 nm	6.7	7.3	16.9	9.0
80 nm	5.8	8.0	22.7	8.0
Slider				
40 nm	6.3	7.4	16.7	8.9
80 nm	6.3	7.0	22.6	8.1
Route				
40 nm	6.2	7.6	16.3	9.1
80 nm	5.3	8.4	21.7	8.1

V. DISCUSSION

In summary, no single method was found to be the clear winner based on the performance results. Pilots appeared to be able to evaluate predictive weather forecasts and plan trajectory modification about equally well using any of the methods. The only performance difference specifically related to the methods per se was in the total time taken for evaluation and modification; there, the Route method showed a small

TABLE 6. DISTRIBUTION OF PILOT RATINGS ON THE IMPLEMENTATION AND UTILITY OF THE METHODS

Viewing Method	***Ratings***				
	1	***2***	***3***	***4***	***5***
Pulse					
Implementation[a]	0.01	0.04	0.06	0.26	0.63
Utility[b]	0.00	0.02	0.00	0.13	0.85
Slider					
Implementation	0.00	0.06	0.07	0.26	0.60
Utility	0.00	0.00	0.02	0.26	0.72
Route					
Implementation	0.00	0.12	0.20	0.30	0.38
Utility	0.00	0.02	0.07	0.39	0.52

a. Implementation ratings from 1 to 5 stand for: very difficult to use, somewhat difficult to use, neither difficult or easy to use, somewhat easy to use, and very easy to use

b. Utility ratings from 1 to 5 stand for: represent useless to have, somewhat useless to have, neither useless or useful to have, somewhat useful to have, and very useful to have advantage when difficult maneuvers were demanded. It is likely that differences afforded by the three methods, primarily in terms of the input method for adjusting predictive ranges, were too small compared to the time spent on deciding the best course of action around weather.

Subjective evaluation results showed the Pulse method to be most favored and Route method least favored. Caution should be taken in evaluating this finding because the Pulse method had the additional pulsing function while the other two did not. It is not difficult to envision that the pulsing function could exist in all three methods regardless of how predictive range is set. In fact, when asked what features they would like to retain if given the choice to freely combine elements from all three, 11 of the 18 pilots requested the pulsing function.

The responsiveness of the interface itself as pilots interacted with it also factored prominently in pilots' subjective experience of the three methods. For example, when asked what they did not like about the Route method, 10 of the 18 pilots voiced dissatisfaction with the speed and smoothness of its operation. While most liked the idea of interacting with the trajectory directly, they found switching between waypoint manipulation and bean (aircraft) position manipulation to be difficult, clunky, and even frustrating. These difficulties from this particular implementation of the Route method likely contributed to the Route method's inferior subjective evaluation.

Although the part-task environment included the minimal amount of setup to simulate en route weather avoidance, and as such may have appeared somewhat unrealistic (e.g., no traffic, no wind information, perfectly accurate prediction), the findings on how path stretch and weather CPA were affected by distance to weather, and by encounter type, suggest that the task environment produced results that are in line with how we might expect pilots to behave around real weather. In fact, here we note one particular finding that potentially sheds light on an aspect of pilot weather avoidance behavior that previously puzzled researchers. DeLaura and Evans examined pilot weather avoidance behavior from actual flights in order to determine deviation strategies and avoidance distances for the purpose of computationally modeling and predicting avoidance decisions [12]. In the paper they acknowledged that not all deviation strategies could be explained by anticipated intensity of weather encounter on the planned trajectory. Specifically, DeLaura and Evans noted a case of weather avoidance where the cause and intent of the deviation were "unclear" (see [12], Figure 10). In this example a pilot made a large deviation around a region of benign weather, more than 100 km downwind from the nearest convection cell (see also [13], Figure 4). A similar strategy of weather avoidance behavior was observed in the present study during some of the "Clear later" scenarios. "Clear later" scenarios were constructed such that the initial trajectory, though appearing obstructed by current weather, would be clear of the projected edge of a line of storms by approximately 10 nm, a margin greater than what pilots sometimes maintain when passing between storm cells. The initial idea behind this type of scenarios was to see how long it would take for the pilots to realize that no modification was necessary using the three viewing methods. A post-hoc examination of these trials shows that on most of these trials pilots still made modifications to keep the trajectories further away from weather, often keeping a 20 nm margin.

The reasoning behind the maneuver observed by DeLaura and Evans [12, 13] may be inexplicable when avoidance decisions are to be interpreted solely based on Vertically Integrated Liquid (VIL) levels and relative radar echo top heights, as in the Convective Weather Avoidance Model (CWAM). However, observations of pilot weather avoidance behavior from the present study showed that pilots routinely modify their flight trajectories to be further away from any radar echo to maintain the 20 nm recommended margin if the opposite side of the airspace is clear of weather. When asked, the pilots commented that the open airspace to the other side afforded them the opportunity, and they simply took advantage of that when they could. This type of weather avoidance strategy suggests that pilots use heuristics to exploit opportunities present in a given encounter, such as this one for increasing a safety margin,.

Needless to say, there were other elements critical to en route weather avoidance not represented in the current part-task environment. For example, unlike in the real world, in the experiment pilots never had the chance to observe how the weather unfolded and whether their final trajectory continued to be safe as time elapsed. In fact, some pilots described their weather avoidance practice as an iterative process. They usually do not make a complete modification up front but rather make small adjustments and then wait and see how things turn out. This type of strategy could be attributed to the fact that the type of weather information they have access to is often not of predictive nature and therefore planning well in advance may not be productive. It also suggests that a method like the Route method could be of great value when pilots want to monitor the relationship of ownship to that of weather at a specific location in space ahead. Likewise, the pulsing function offered in the Pulse method could be very useful for visualizing predicted traffic congestion in the surrounding airspace if the positions of all aircraft could pulse together.

VI. IMPLICATION ON ATM WEATHER INTEGRATION

As discussed previously, flight decks and ATCs make different types of weather decisions, which require different types and formats of information. Hence, the results found here from the evaluation of flight deck display interfaces may not have direct implications for ATC weather displays. Findings from the present experiment on pilot weather avoidance behavior in general, however, could inform research on modeling en route weather avoidance behavior. Our results suggest that pilot weather avoidance strategy is affected by distance to weather. The predictive weather forecasts provided in the experiment allowed pilots to preview the weather as far as 320 nm ahead while common airborne weather radars have a useful range between 30 to 80 nm. Models developed to predict weather avoidance behavior, such as CWAM [12, 13], that are based on flight data from aircraft equipped with current day weather sensing technologies, may not be applicable to predict behaviors of pilots with access to long range predictive forecasts. Indeed, as Evans [14] noted, pilots' deviation decisions are affected by their estimate of their aircraft's altitude relative to the storm top, and it can be difficult for them to generate reliable estimates when their aircraft is 20-40 nm away from the storms. He recommended providing ground derived storm information to the cockpit to elicit consistent deviation behavior from different pilots and consequently improve the ability to predict pilot deviation decisions. Our results offer an empirical glimpse at how pilot weather decisions might differ according to the range of available information.

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REFERENCES

[1] Joint Planning and Development Office, Concept of Operations for the Next Generation Air Transportation System, Version 3.2, September 2010.

[2] M. P. Kay, "An analysis of collaborative convective forecast product performance for the 2005 convective season," *Proc. 12th Converence on Aviation, Range, and Aerospace*, Januray 2006.

[3] T. Fahey, and D. Rodenhuis, "Continual evolution of CCFP – User needs for extended range prediction," *Proc. 11th Conference on Aviation, Range, and Aerospace Meteorology*, October 2004.

[4] National Oceantic and Atmospheric Association's National Weather Service, Aviation Weather Center, "Collaborative Convection Forecast Product: Product description document," retrieved from the web on January 23, 2011. http://aviationweather.gov/products/ccfp/docs/pdd-ccfp.pdf

[5] D. L. Sims, R. Wise, T. Yuditsky, S. McGettigan, and P. J. Smith, "More intuitive graphics for Collaborative Convective Forecast Product (CCFP)," *Proc. 11th Conference on Avation, Range, and Aerospace Meteorology*, October 2004.

[6] J. Lachter, V. Battiste, R. Koteskey, A.-Q., Dao, S. L. Brandt., S. V. Ligda, S.-C., Wu, and W. W. Johnson, "Issues for near-term implementation of trajectory based operations," Paper to be presented at the Ninth USA/Europe Air Traffic Management Research and Development Seminars, 2011.

[7] J. Rasmussen, and K. J. Vicente, "Coping with human errors through system design: Implications for ecological interface design," *Int. J. Man-Machine Studies*, vol. 31, pp. 517-534, 1989.

[8] K. J. Vicente, and J. Rasmussen, "The ecology of human-machine system II: Mediating 'Direct Perception' in complex work domains," *Ecological Psychology*, vol. 2, pp. 207-249, 1990.

[9] K. J. Vicente, and J. Rasmussen, "Ecological interface design: Theoretical foundations," IEEE Trans. Sys. Man. Cyber., vol. 22, pp. 589-606, 1992.

[10] K. J. Vicente, "Ecological interface design: Progress and challenges," *Human Factors*, vol. 44, pp. 62-78, 2002.

[11] M. Mulder, R. Winterberg, M. M. van Paassen, and M. Mulder, "Direct manipulation interfaces for in-flight four-dimensional navigation planning," *Int. J. Aviation Psychology*, vol. 20, pp. 249-268, 2010.

[12] R. DeLaura, and J. Evans, "An exploratory study of modeling enroute pilot convective storm flight deviation behavior," *Proc. 12th Conference on Aviation, Range, and Aerospace Meteorology*, 2006.

[13] R. DeLaura, M. Robinson, M. Pawlak, and J. Evans, "Modeling convective weather avoidance in enroute airspace," *Proc. 13th Conference on Aviation, Range, and Aerospace Meteorology*, January 2008.

[14] J. E. Evans, "Key research issues for near term operational use of integrated convective weather-ATM decision support system," *Proc. 13th Conference on Aviation, Range, and Aerospace Meteorology*, January 2008.

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