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Controller Scan-Path Behavior During Severe Weather Avoidance

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16. Abstract

In the present study, we examined controllers' fixation behavior on Storm Motion tools during severe weather avoidance. The data consisted of eye movement recordings from time intervals when controllers activated a static or a dynamic Storm Motion tool. Both of these tools provided information about the direction of storm cell motion and future extrapolated positions of the storm cell leading edge. By analyzing the location and extent of fixations, we performed an assessment to identify the static weather tool features that captured controllers' visual attention (i.e., areas of visual interest). Second, we analyzed controller scan path behavior (a series of fixations and saccades) while they were using the static and the dynamic tools. Third, we assessed controller fixation prioritization strategies during static tool usage. Our analysis revealed that controllers focused their visual attention significantly more on the area between the storm cell leading edge and the 10 minute extrapolated position compared to other areas of the static Storm Motion tool. With regards to controller scan paths, we found that dynamic Storm Motion tools significantly reduced controller scan path areas, scan path distances, and scan path durations compared to the static tool. Furthermore, the mean pupil diameter was significantly larger for controllers while using the static tool compared to the dynamic tool, indicating a higher visual and cognitive workload during this display condition. We found little evidence for systematic controller fixation behavior while they were using the static tool. The few systematic patterns that we revealed were two-step fixation patterns (e.g., aircraft → 10 minute extrapolated position), and the vast majority of fixation orders (patterns) were unique to each individual controller. Evidently, the static Storm Motion tool provided weak affordances to controllers during tactical operations. We discuss these results in relation to the attentional capture phenomenon and suggest possible ways to improve static Storm Motion tools for tactical operations.

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Executive Summary

Information displays are currently used in many new areas including the presentation of aviation and air traffic control (ATC) related weather information (Ahlstrom & Della Rocco, 2003). Although weather visualizations have a long tradition in meteorology and weather forecasting, much less is known about how to create efficient weather displays for ATC operations. In current ATC operations, traffic management and supervisors use weather information primarily for planning purposes. Their aim is to grasp the big weather picture, identify important trends and patterns, and use this information to plan future actions. However, controllers use weather information in an environment where the focus is on tactical thinking. Therefore, they need tactical weather tools to make safe and efficient decisions that support the hands-on, moment-to-moment management of air traffic within the airspace (Ahlstrom, 2005). The question is what type of temporal format (static versus dynamic) and display representation (text versus graphics) produces the most efficient design for use in tactical operations.

Eye movement guidance on information displays is an active process of exploring display regions for goal-relevant information. Therefore, we might use eye movement analysis as an objective method for assessing the location of meaningful content in an information display. In the present study, we examined controllers' fixation behavior on Storm Motion tools during severe weather avoidance. The data consisted of eye movement recordings from time intervals when controllers activated a static or a dynamic Storm Motion tool. Both of these tools provided information about the direction of storm cell motion and future extrapolated positions of the storm cell leading edge. By analyzing the location and extent of fixations, we performed an assessment to identify the static weather tool features that captured controllers' visual attention (i.e., areas of visual interest). Second, we analyzed controller scan path behavior (a series of fixations and saccades) while they were using the static and the dynamic tools. Third, we assessed controller fixation prioritization strategies during static tool usage.

Our results showed that controllers focused their visual attention significantly more on the area between the storm cell leading edge and the 10 minute extrapolated position compared to other areas of the static Storm Motion tool. With regards to controller scan paths, we found that dynamic Storm Motion tools significantly reduced controller scan path areas, scan path distances, and scan path durations compared to the static tool. Furthermore, the mean pupil diameter was significantly smaller for controllers while using the dynamic tool compared to the static tool, indicating a lower visual and cognitive workload during the dynamic condition. We found little evidence for systematic controller fixation behavior while they were using the static tool. The few systematic patterns that we revealed were two-step fixation patterns (e.g., aircraft → 10 minute extrapolated position), and the vast majority of fixation orders (patterns) were unique to each individual controller.

In our static Storm Motion display, the activation caused the appearance of tool features on storm cells throughout the display. This abrupt onset captured controllers' attention and resulted in significantly larger scan path areas, scan path distances, and scan path durations compared to when controllers were using the dynamic tool. Furthermore, controllers had significantly larger pupil diameters when using static tools compared to dynamic tools, which is indicative of higher visual and cognitive workload (Van Orden, Limbert, Makeig, & Jung, 2001). Therefore, rather than facilitating and enhancing controller scan path behavior, the static tool interrupted goal-directed exploration and produced less efficient scan path behavior. We hypothesize that the

static tool may have less negative effect on scan path behavior if it is displayed in smaller areas on the situation display. For example, rather than displaying all available Storm Motion information on cells throughout the situation display, it should be possible to define and tailor the presentation of this information to cover smaller, but more relevant areas. Furthermore, by only displaying elements that define the area between the storm cell leading edge and the 10 minute extrapolated position, it might be possible to enhance controller information pick-up during tactical operations even further while reducing attentional capture.

We conclude, given what we know now, that animated storm predictions are more suitable for tactical ATC operations, as compared to static element-based representations. By using this display principle when designing future Storm Motion displays, we should be able to create weather tools that increase controller efficiency and safety during weather avoidance in tactical ATC.

1. INTRODUCTION

A key issue in the design of modern information displays is how to visually present complex system information to operators. Examples of domains where operators rely on visually complex information displays are nuclear power plants, manufacturing systems, and air traffic control (ATC) systems (Vicente & Rasmussen, 1990). Depending on the system and the degree of operator interaction, displaying various information sources like system data, status symbols, warnings, messages, and advisories, can be a design challenge, because these display objects must be readily available for the operator to maintain efficient and safe control. Also, with an increasing amount of display data there are other human factors challenges like legibility and salience manipulation that designers must resolve (Ahlstrom & Arend, 2005).

Information displays are currently used in many new areas including the presentation of aviation and ATC related weather information (Ahlstrom & Della Rocco, 2003; Arend, 2003). Although weather visualizations have a long tradition in meteorology and weather forecasting, there is a need to refine this information for use in modern information displays (Trafton & Hoffman, in press). Also, other issues like the use of temporal format (static versus dynamic) and display object representation (text versus graphics) can also be problematic in the design of information displays (Oron-Gilad, Meyer, & Gopher, 2001; Sanderson, Pipingas, Danieli, & Silberstein, 2003). With regards to the temporal format, there is currently conflicting evidence regarding the ease of use for both static and dynamic weather visualizations. While it seems like weather forecasters can build dynamic mental models of weather patterns using static image information (Bogacz & Trafton, 2005), there is evidence that students of meteorology for example, frequently have a difficult time in making effective use of static weather maps (Lowe, 2003). There are also other issues regarding dynamic weather visualizations. For instance, meteorology students typically extract the information that is perceptually salient, but tend to neglect the low-salience features that convey important meteorological information. This leads us to the question as to what constitutes informative properties in weather visualizations. It also raises questions regarding how we should display these properties to operators so that it results in optimal information extraction.

In current ATC operations, traffic management and supervisors use most of the available weather information for planning purposes. For these uses, the focus is on *strategic* thinking: the systematic use of weather information to foresee and manage operations, increase efficiency, and to provide better service for the flying public during adverse weather conditions. The aim of strategic thinking is to grasp the big weather picture, identify important trends and patterns, and use this information to plan future actions. However, controllers use weather information in an environment where the focus is on *tactical* thinking. Therefore, they need tactical weather tools to make safe and efficient decisions that support the hands-on, moment-to-moment management of air traffic within the airspace (Ahlstrom, 2005). Regarding severe weather avoidance in ATC, the strategic use of weather information is related to the “what” and “why” and the tactical use of weather information is related to the “how” (for a discussion of strategic versus tactical weather behavior among pilots, see Latorella & Chamberlain, 2002).

Determining the optimal presentation format of advanced weather information for controllers is a relatively new research area, and no *tactical* weather displays are currently in use. Controllers are not meteorologists and unlike expert weather forecasters, their primary responsibility is not to provide weather forecasts but to direct the real-time movement of aircraft while maintaining safe separation within their sectors. Second, unlike meteorologists and expert weather forecasters, the controller's weather information requirements are driven by tactical needs, not strategic needs. We assume that this requirement for tactical use is likely to increase the need for the delivery of timely and easily extracted goal-relevant weather information. While meteorologists and forecasters use weather visualizations, it is unknown whether their tools use the most appropriate format to meet the tactical requirements of controllers. With this analysis, we hope to identify characteristics of weather visualizations that are most useful for tactical controllers.

In a recent high-fidelity human-in-the-loop simulation, we found that terminal controllers improved sector throughput when using advanced weather tools (Ahlstrom & Friedman-Berg, 2005). During these severe weather avoidance scenarios, controllers most frequently used tools that provided information about future storm cell positions. Controllers had access to three different prototype tools for the prediction of storm cell movements; two were dynamic in nature while the third was a static visualization. The results showed that controllers activated (used) dynamic tools more frequently than static tools. Currently, static Storm Motion tools are included in the Integrated Terminal Weather System (ITWS; Evans & Ducot, 1994) which is used for strategic purposes by traffic management and supervisor in the terminal domain. Dynamic storm tools are not available for current ATC field operations, although such tools are included in the Corridor Integrated Weather System (CIWS; Evans, et al., 2004) currently under assessment. Because our goal is to develop storm prediction tools specifically designed for tactical ATC operations, in the current analysis we wanted to evaluate the design and the use of these tools in more detail.

Commonly, when researchers perform human-in-the-loop simulations they collect subjective data in the form of oral reports, debriefings, and questionnaires. Although this data is valuable and informative, these sources have several limitations relating to the assessment of the design and use of tactical weather tools. For example, predictive weather tools provide useful information (i.e., affordances) of future opportunities for the movement of traffic within the sector while avoiding heavy weather cells. However, while controllers may act on these visual affordances when controlling traffic, they may be unable to provide retrospective verbal reports about how they used these affordances during a simulation. This is because the perception of affordances is direct (Vicente & Rasmussen, 1990); there are no intermediate stages between the specification of weather tool affordances and the perception of these affordances. Therefore, researchers must be careful when investigating display affordances by means of subjective verbal reports (Pepping & Li, 2005).

Eye movement guidance on information displays is an active process of exploring display regions for goal-relevant information (Brockmole & Henderson, in press). Therefore, we might use eye movement analysis as an objective method for assessing the location of meaningful content in an information display. Specifically, researchers have used point-of-gaze (POG) data to define fixations and areas-of-interest (AOI) to determine how viewers examine images and displays (Santella & DeCarlo, 2004). For instance, we may use an analysis of eye movements to identify those object locations and object features that attract the viewers' focal attention. Furthermore, if we design display objects with the purpose of providing visual affordances to viewers, then we can analyze their fixation behavior to draw conclusions about the effectiveness of the design (Renshaw, Finlay, Ward, & Tyfa, 2003). For example, in some designs the distinctive aspects of display objects grab the viewers' attention (i.e., attention capture) even though they are irrelevant to the task. This can negatively impact viewer's visual attention allocation during time-critical assessments, because attention capture interrupts goal-directed eye movements (Brockmole & Henderson). As an example, in a study on the interpretation of weather graphics, Canham and Hegarty (2004) demonstrated that naïve viewers initially directed their focal attention (i.e., eye fixations) towards task-irrelevant features of the display, but after a limited amount of instruction redirected their attention toward more relevant aspects of the weather display.

We can analyze sequences of eye movements and fixations (i.e., scan paths) to evaluate different display designs. Goldberg and Kotval (1999) proposed that scan path metrics like scan path length and scan path area can inform usability studies by helping to differentiate good and bad display designs. Goldberg and Kotval concluded that poorly designed interfaces lead to longer and more widely distributed scan paths.

In the present study, we examined controllers' fixation behavior on static weather tool features using eye movement recordings. First, by analyzing the location and extent of fixations, we performed an assessment to identify the weather tool features that captured controllers' visual attention. Second, we analyzed the duration of tool fixations for static and dynamic tools. Third, we assessed fixation prioritization strategies used by controllers during their weather tool usage. Using this analysis, we attempted to identify hidden patterns in controllers' fixations on different weather tool details, traffic, and sector map during tool activation. Taken together, the current analyses will provide valuable information to help researchers design Storm Motion tools optimized for tactical weather avoidance.

2. METHOD

For the present study, we used oculometer recordings from a simulation of severe weather avoidance in a generic terminal airspace (Ahlstrom and Friedman-Berg, 2005). Because the focus here is solely on the eye-movement data from this simulation, we only present a brief summary of the simulation design. For a complete description of the simulation setup, weather scenarios, procedure, and simulation results, see Ahlstrom & Friedman-Berg.

2.1 Participants

Eleven non-supervisory, full-performance level Terminal Radar Approach Control (TRACON) controllers volunteered as participants in the simulation (mean job experience =12 years).

2.2 Simulation Setup and Procedure

During the simulation, we used a high-fidelity simulator that emulates the Standard Terminal Automation Replacement System (STARS) used in select TRACONs. We used a generic TRACON airspace with two adjacent sectors and six 50-min traffic scenarios with a moderate traffic level. During the simulation, two controllers operated traffic within the airspace. One controller was responsible for West operations, while the other controller was responsible for East operations. The West side controller wore an oculometer consisting of an eye and head tracking system, Applied Sciences Laboratory Series 6000 Model 501 (Applied Science Laboratories, Inc., 2004).

We presented weather information (in addition to precipitation information) either directly on the controller workstation, or on an auxiliary Weather Information Display System (WIDS: Ahlstrom, Keen, & Mieskolainen, 2004) located on top of the controller workstation (see Figure 1). The weather information consisted of pre-recorded ITWS data and prototypes of dynamic predictions of storm movements. Two 50-min weather samples of pre-recorded ITWS data were used in the simulation. Both weather scenarios contained the same precipitation, storm motion, gust front, wind shear, and microburst information. The only differences between weather scenarios were the overall spatial and temporal movements. To tailor the operating procedures for the simulation, we included a severe weather avoidance procedure that assigned responsibility for keeping aircraft away from weather Levels 4, 5, and 6, to the controller.

Figure 1. Simulation setup with the STARS controller workstation (bottom) and the WIDS display (top). The researcher in the figure is wearing the Applied Sciences Laboratory Series 6000 Model 501 eye and head tracking system used during the simulation.

We manipulated three independent variables during the simulation: 3 (display location of advanced weather information) x 2 (weather scenario) x 2 (sector position). Each controller participated in all six conditions. We counterbalanced the presentation order of the simulation conditions by means of a randomized block design. In the first simulation condition, we displayed weather information on an auxiliary weather display. In the second condition, we displayed weather information directly on the controller workstation. The controllers did not use the auxiliary weather display during this condition. In the third condition, we did not present any advanced weather information to the controller, nor was the auxiliary weather display used during this condition. This condition represents current TRACON operations in the field. However, during all simulation conditions, controllers had access to six levels of precipitation similar to what they currently use for STARS operations. For the present analysis, we only used data from the second condition.

During all runs, the controllers provided workload ratings using the Air Traffic Workload Input Technique (ATWIT; Stein, 1985). The system prompted controllers for input every five minutes by emitting several beeps and lighting ten buttons on a keypad. The controllers indicated their instantaneous workload by pressing one of the keypad buttons labeled from 1 to 10.

2.3 Oculometer Recordings

Our head mounted eye tracker system integrates eye and head position data to measure a person's POG with respect to a fixed scene plane. During the simulation, we defined a calibration plane and four other bounded planes corresponding to the main situation display, the auxiliary WIDS display, the strip bay, and the keyboard. For human subjects and normal viewing conditions, the spatial error between the true eye position and the computed eye position is less than .5 degrees. During the simulation, we recorded the eye's position in vertical and horizontal coordinates and the pupil diameter every 60^{th} of a second (60 Hz). The software computed a fixation as the mean x and y eye position coordinates measured by the maximum change in a gaze point of 1 degree of visual angle with a minimum duration of 100 msec. POG recordings with larger angles and shorter durations were defined as saccades (Applied Science Laboratories, Inc., 2004).

2.4 Analysis Software

We performed our fixation analysis on the eye movement and pupil diameter information recorded in the simulation eye-tracking data (Applied Science Laboratories, Inc., 2004). The oculometer software (Eyehead™) enables integration of eye and head position data to compute POG, identify eye fixations, match fixations with designated AOIs on the scene plane, and calculate related scan pattern statistics. The software also allows for the plotting of fixations and AOIs directly onto screen captures from actual simulation recordings. Because we only collected oculometer data for the West controllers, we only use their data in the current analysis.

For the detection and analysis of hidden patterns in controllers' fixations behavior, we used the Theme™ software tool (PatternVision Ltd and Noldus Information Technology bv, 2004). The Theme™ software detects very general patterns (T-patterns; Magnusson, 2000) by performing a structural analysis of the fixation data. During this analysis, the tool detects the order of events (e.g., the temporal order of feature fixations) and the hierarchical organization of these events. The benefit of Theme™ is that it can detect repeated complex patterns that would otherwise be difficult to detect during a visual data inspection.

For our analysis of scan path area we used MATLAB® (The MathWorks Inc., 2004).

2.5 Static and Dynamic Storm Motion Tools

The purpose of the present study was to answer three important questions about the use of storm tools during severe weather avoidance. First, where does the controller look while using the Storm Motion tools? Second, for how long does the controller attend to each visual element in the display? And third, in what temporal order does the controller attend to the different visual elements of the display?

Two Storm Motion tools were available to controllers during the simulation, one static and one dynamic. Both tools provided extrapolated positions for future storm cell locations. The static tool provided extrapolated positions for 10 and 20 minutes, while the dynamic tool used an extrapolated position for 15 minutes. Although the extrapolated positions were different, users could interpolate between these linear extrapolations to infer future storm positions.

The static Storm Motion tool consisted of the five separate features illustrated in Figure 2. The vector indicated the direction of cell motion, and the numerals indicated the speed of the storm cell in knots. Motion estimates were produced for all level three or greater cells and displayed on the area of heaviest precipitation within the cell. A solid line indicated the leading edge of a storm cell, and a broken and a dotted line showed the 10- and 20-minute extrapolated positions for the leading edge, respectively. When controllers activated the static Storm Motion tool (toolbar button press), all five features were displayed simultaneously. There was no option for controllers to select individual display features. The system continued to display the static Storm Motion tool until the controller deactivated the tool with a second button press.

Figure 2. Illustration of the static Storm Motion tool. The vector (arrow) indicates the direction of cell motion, and the numerals indicate the cell speed in knots. The solid blue line depicts the storm cell leading edge, the broken blue line depicts the 10 minute extrapolated position, and the dotted blue line depicts the 20 minute extrapolated position.

The activation of the dynamic Storm Motion tool using a toolbar button press resulted in a dynamic sequence where the current precipitation areas (Figure 3) moved to an extrapolated position 15 minutes into the future (Figure 4). In essence, the dynamic version moved the precipitation areas instead of displaying the vector and numerals, a leading edge, and two extrapolated positions. Upon activation, the system displayed the extrapolated positions for two seconds and then returned the precipitation areas to their current position. Each additional button press by the controller displayed the dynamic Storm Motion tool for an additional two seconds, making it possible to view the sequence for as long as necessary. Figure 3 shows an example depicting the current location of a storm cell. The red dot represents the storm cell leading edge as shown in Figure 2. This dot was *not visible* in the simulation displays, but we display it here for illustrative purposes. Upon activation, the storm cell leading edge (red dot) moves to a position 15 minutes into the future (Figure 4).

Figure 3. An illustration of the dynamic Storm Motion tool before activation. The red dot illustrates the leading edge of the storm cell shown in Figure 2.

Figure 4. An illustration of the Dynamic Storm Motion tool after activation. The leading edge of the storm cell (red dot) together with all selected precipitation areas (solid and dotted areas) are extrapolated to a position 15 minutes into the future.

3. RESULTS

3.1 Static and Dynamic Tool Usage

During the human-in-the-loop simulation, the eleven controllers used the dynamic Storm Motion tool more frequently than the static Storm Motion tool. In fact, about 53% of all weather tool activations were for the dynamic Storm Motion tools compared to only 12% for the static Storm Motion tool. The remaining 35% were for activations of other tools not discussed here (Ahlstrom & Friedman-Berg, 2005). Figure 5 shows the mean number of tool activations for the static and the dynamic Storm Motion tools by the West controllers. As expected, there were significantly more activations per weather scenario for the dynamic tool compared to the static tool ($t(4) = 2.23$, $p = .045$, one-tailed). However, there was no significant difference in the mean number of fixations per second during the time these two tools were activated (see Figure 6).

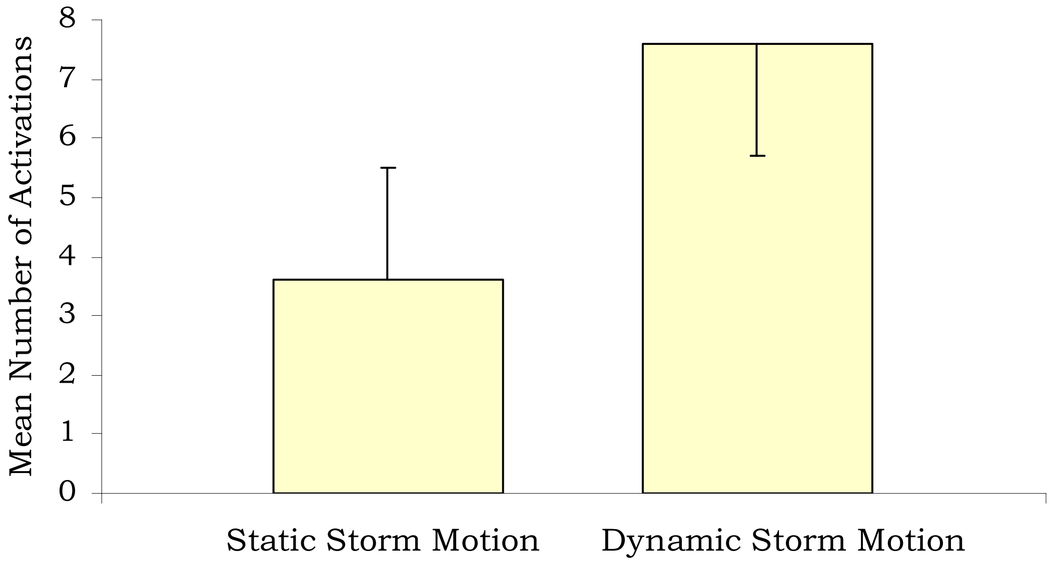

Figure 5. Mean number of activations per weather scenario for the static and dynamic Storm Motion tools. Error bars are 95% one-tailed within-subject confidence intervals (*CI*s; Cousineau, 2005; Loftus & Masson, 1994).

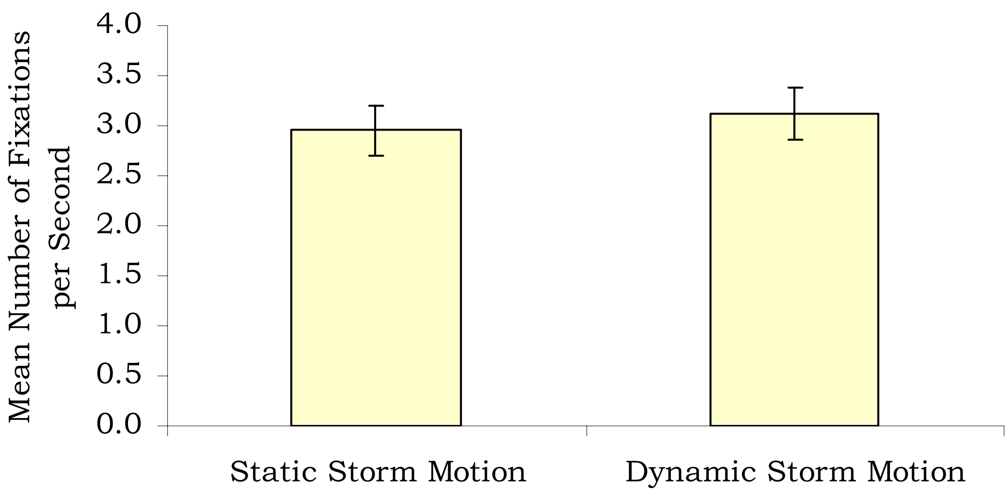

Figure 6. Mean number of fixations (per second) for the static and dynamic Storm Motion tools. Error bars are 95% within-subject *CI*s.

3.2 Fixation Pattern Order Analysis

For the present analysis, we focused on a fixation pattern analysis for the static Storm Motion tool. Our overall aim was to assess possible ways to improve the static Storm Motion tool for tactical operations. The static tool had five display elements, and we wanted to assess whether all elements were of equal visual interest to controllers, or if only some of them attracted the controllers' focal attention. The dynamic tool had no display elements for storm cell speed and direction, and no display elements for current and extrapolated positions for future locations. It provides this information simply by extrapolating (moving) all precipitation levels to a location 15 minutes into the future. Therefore, we did not perform this analysis for the dynamic tool conditions.

We attempted to identify different patterns of fixations on the different display elements by (a) coding fixations for aircraft , (b) airspace, (c) precipitation, (d) vector and speed numerals, (e) leading edge, (f) 10 min extrapolated position, and (g) 20 min extrapolated position. We wanted to determine whether controllers fixated different elements of the static Storm Motion tool in a prototypical order, whether the controllers fixated certain display elements combinations repeatedly, or whether fixation patterns were random. For every instance of static Storm Motion activation, we identified all display features within a two inch diameter of each fixation (see Figure 7), ranking them in order from the nearest to the farthest. We then used the Theme™ software tool to search for any hidden patterns in controllers' fixations (Magnusson, 2000). We analyzed the data three ways: 1) including all display features within the two inch diameter (coded for distance from the fixation), 2) including only the two features nearest to the fixation, and 3) including the single feature nearest to the fixation (Mulligan, 2001). Because the number of patterns detected using the first and second method were in the thousands, indicating a lack of a systematic pattern usage, we only report the results from the third analysis.

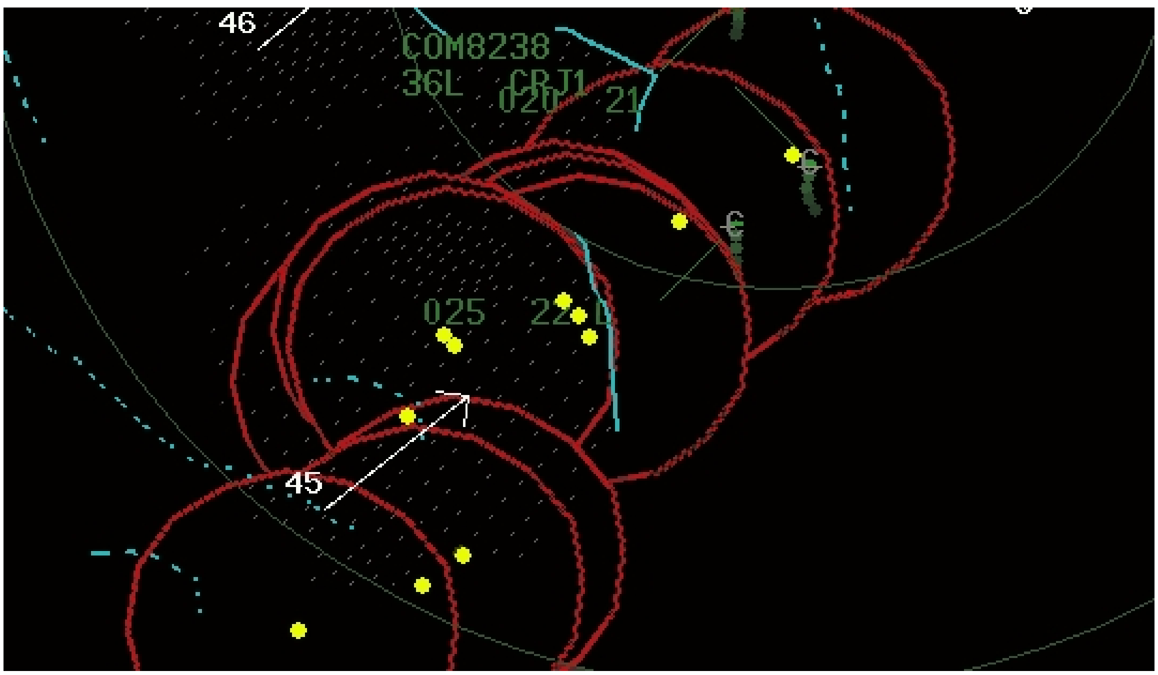

Figure 7. A graphical illustration of the analysis of static Storm Motion tool components and display features within a two inch diameter (red circle) from each fixation (yellow dot).

To perform this analysis, we ran each individual controller's data through the Theme™ software to identify subject-specific fixation patterns. After identifying subject-specific patterns, we then identified those fixation patterns that occurred for more than one controller (across-subject patterns). For these across-subject patterns, we calculated the average number of repetitions for each fixation pattern, averaging across only those controllers who exhibited that pattern. It is clear from looking at

Figure 8 that the majority of the fixation patterns consist of controllers fixating at an aircraft, then fixating a weather feature, or fixating a weather feature, then fixating an aircraft. In addition, six of the seven patterns are two-fixation patterns, while only one pattern is a three-fixation pattern.

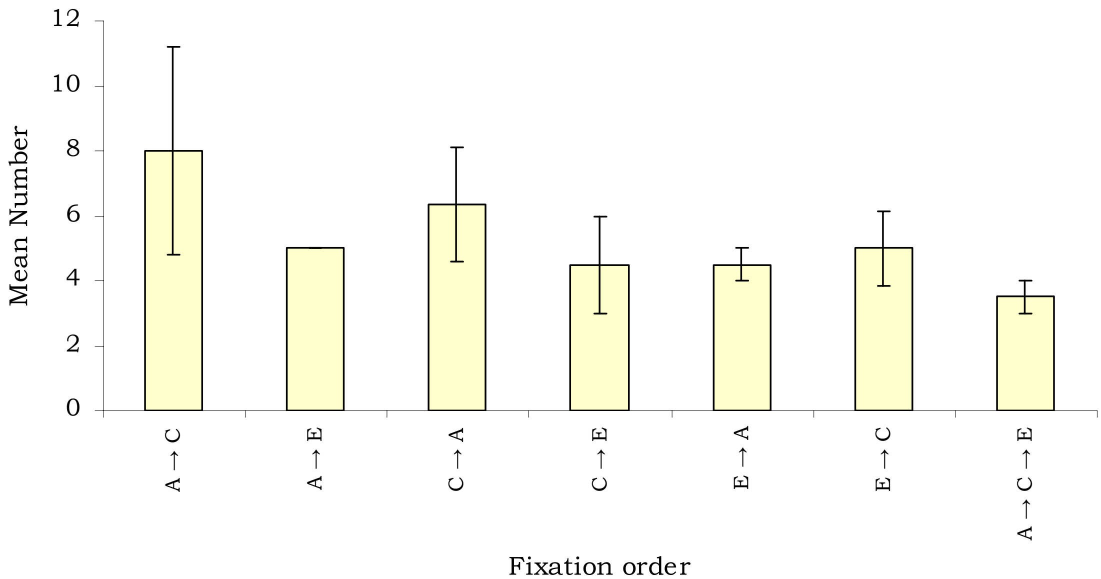

Figure 8. Mean number of fixation orders for the static Storm Motion tool. The fixation order labels are: A = Aircraft, C = Precipitation, E = Leading edge, The error bars are one standard error (*SE*) of the mean.

To sum up, we found little evidence for a systematic fixation behavior for controllers while they used the static Storm Motion tool. Specifically, we were surprised to find so little evidence of systematic higher-order (4 and 5) fixation patterns. The few systematic patterns that we revealed during the analysis were two-fixation patterns, and the vast majority of fixation order patterns were unique to each controller. Evidently, the static Storm Motion tool provided weak affordances to controllers during tactical operations.

3.3 Scan Path Area Analysis

We analyzed the scan paths of controllers when they were using both static and dynamic Storm Motion tools to assess whether there were any differences in their scan path behavior (Goldberg & Kotval, 1999). Goldberg and Kotval theorized that when information layout is good, viewers exhibit a close clustering in their fixation patterns, resulting in smaller scan path areas. However, when information layout is poor, fixations will be more diffuse, resulting in larger scan path areas. Therefore, we computed a measure of scan path area for each instance of static and dynamic Storm Motion tool activation. Using a convex hull function (The MathWorks Inc., 2004), we computed the indices of the fixation points that made up the convex hull (area) for each data set. Figure 9 shows examples of the scan path area for a static (left) and a dynamic (right) data set. Each example consists of 12 consecutive fixations (blue dots). The red line is the computed convex hull for each data set, equaling the scan path area in relative display units (square inches).

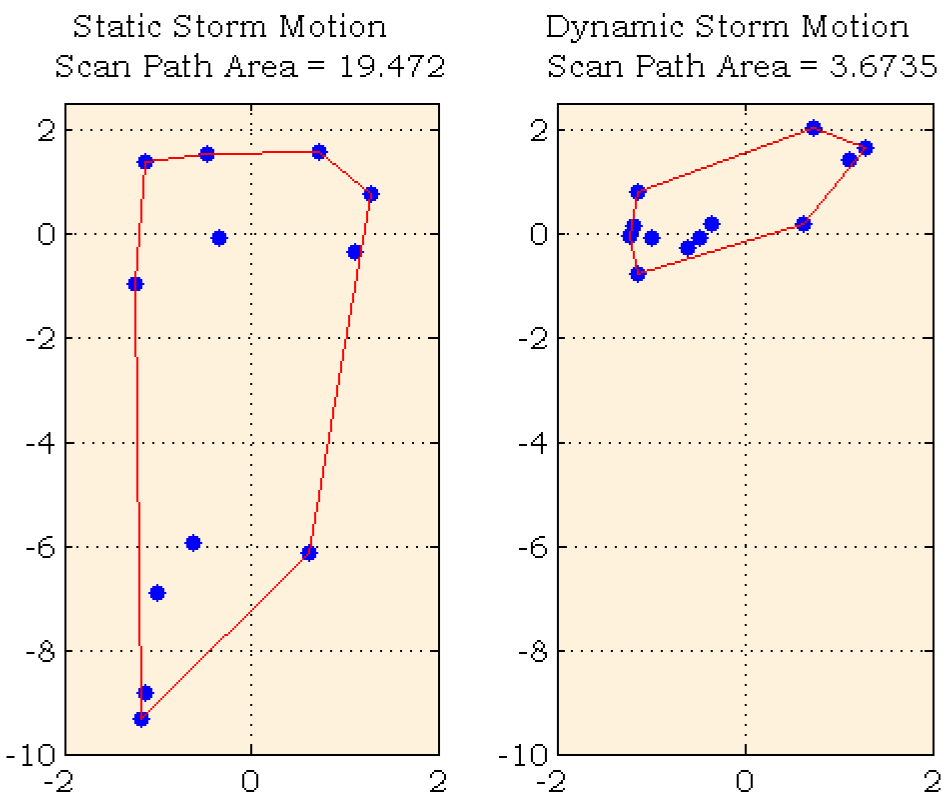

Figure 9. Examples of controller scan path areas. The figure shows the convex hull area (red line) when using static (left) and dynamic (right) Storm Motion tools. Each area is computed from 12 consecutive fixations (blue dots).

To assess whether there was a difference in scan path behavior for static and dynamic tools, we computed the scan path areas for the static and the dynamic Storm Motion tool, using the scan paths recorded while the controller had the tools activated on the display. Figure 10 shows the mean scan path areas when using the static and the dynamic Storm Motion tools. In Figure 10, the mean scan path area for the static tool was significantly larger than the scan path area for the dynamic tool ($t(4) = 4.07$, $p = .015$, two-tailed). Using the static tool appeared to result in more widely distributed scan paths. As stated previously, this is a phenomenon usually interpreted as being an artifact of poorly designed interfaces (Goldberg & Kotval, 1999).

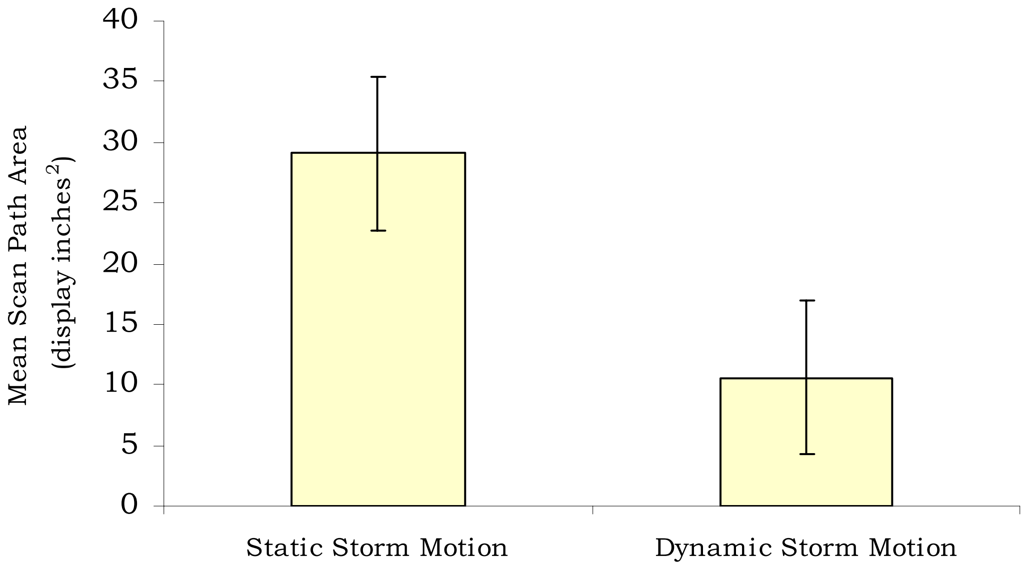

Figure 10. Mean scan path area (display inches^2) for the static and dynamic Storm Motion tools. Error bars are within-subjects *CI*s.

Goldberg and Kotval (1999) also argued that good display design should lead to more optimal searches for relevant information, with less good designs leading to less optimal search sequences. Consequently, the mean scan path distance for well-designed displays should be shorter than the mean scan path distance for less well-designed displays. Therefore, we calculated the mean scan path distance for all instances of static and dynamic Storm Motion tool activations for each participant to determine which tool type resulted in a more optimal search, as measured by scan path distance. In Figure 11, the mean scan path distance for the static tool was significantly longer than the mean scan path distance for the dynamic tool ($t(4) = 4.78$, $p = .008$, two-tailed). This indicates that controllers performed more optimal searches when using the dynamic Storm Motion tool than when using the static Storm Motion tool.

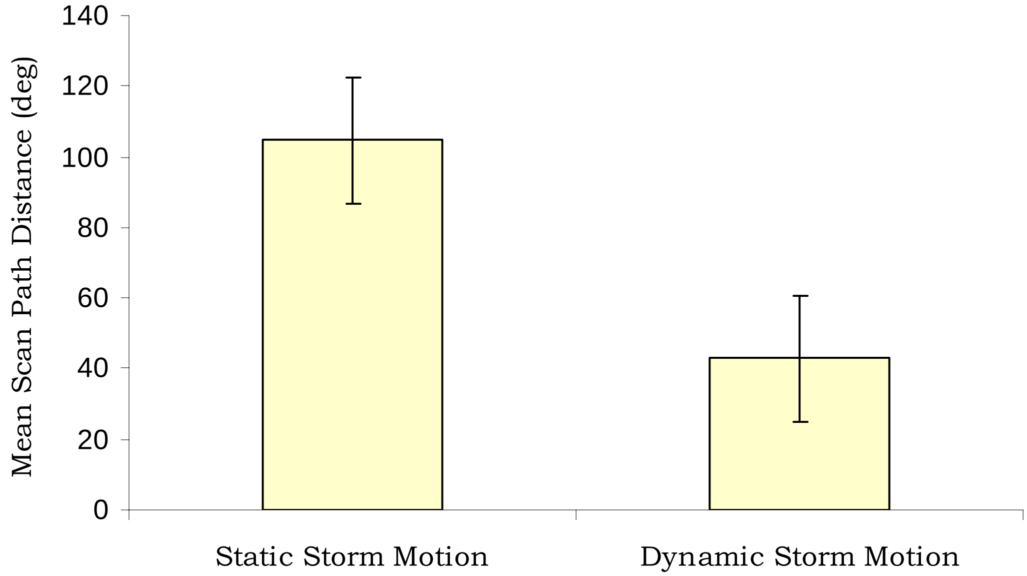

Figure 11. Mean scan path distance (degrees) for the static and dynamic Storm Motion tools. Error bars are 95% within-subject *CI*s.

We also calculated the scan path duration by adding together the duration of all fixations and saccades that form a scan path. Fixation durations contribute a greater proportion of this sum than saccade durations, because fixations are inherently longer than saccades. Therefore, Goldberg and Kotval (1999) present scan path duration as a measure of processing complexity, with greater scan path duration corresponding to greater processing complexity. Phrased in terms of display affordances, we can expect greater scan path durations for less optimal display designs that fail to provide affordances to the viewer. In Figure 12, the mean scan path duration for the static tool is significantly longer than the mean duration for the dynamic tool ($t(4) = 4.43$, $p = .011$, two-tailed), indicating that there was greater difficulty in extracting affordances presented by the static tool compared to the dynamic tool.

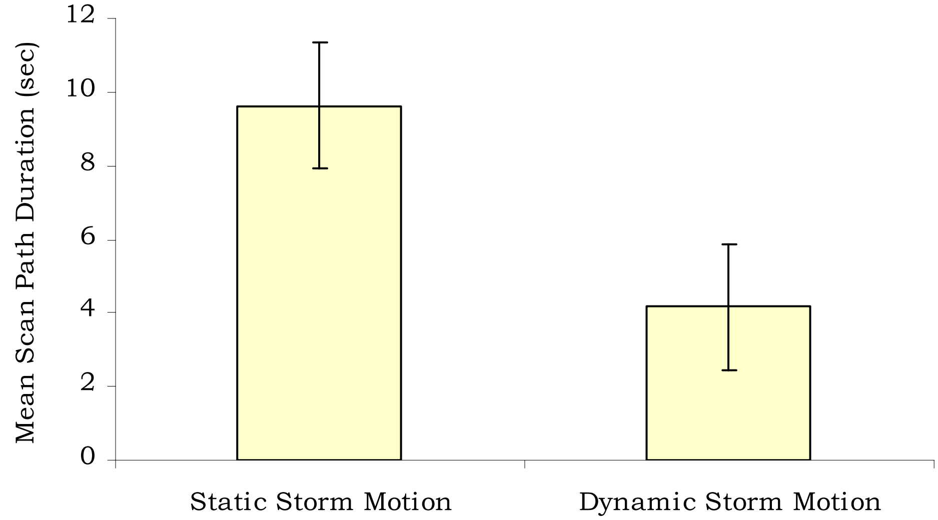

Figure 12. Mean scan path duration (per second) for the static and dynamic Storm Motion tools. Error bars are 95% within-subject *CI*s.

Previous research has shown that different visuospatial tasks affect visual and cognitive workload as measured by eye activity correlates. Specifically, pupil diameter has been shown to generally increase with increasing visual and cognitive demands. For example, Van Orden, Limbert, Makeig, and Jung (2001) found an increase in pupil diameter with increasing display target density during a target identification task. Therefore, we performed an analysis of the pupil diameter for each controller while using the static and the dynamic Storm Motion tools. The mean pupil diameter was significantly larger for the static tool condition compared to the dynamic tool condition ($t(4) = 4.78$, $p = .008$, two-tailed) (Figure 13). Evidently, using the static Storm Motion tool increases visual and cognitive demands compared to using the dynamic tool.

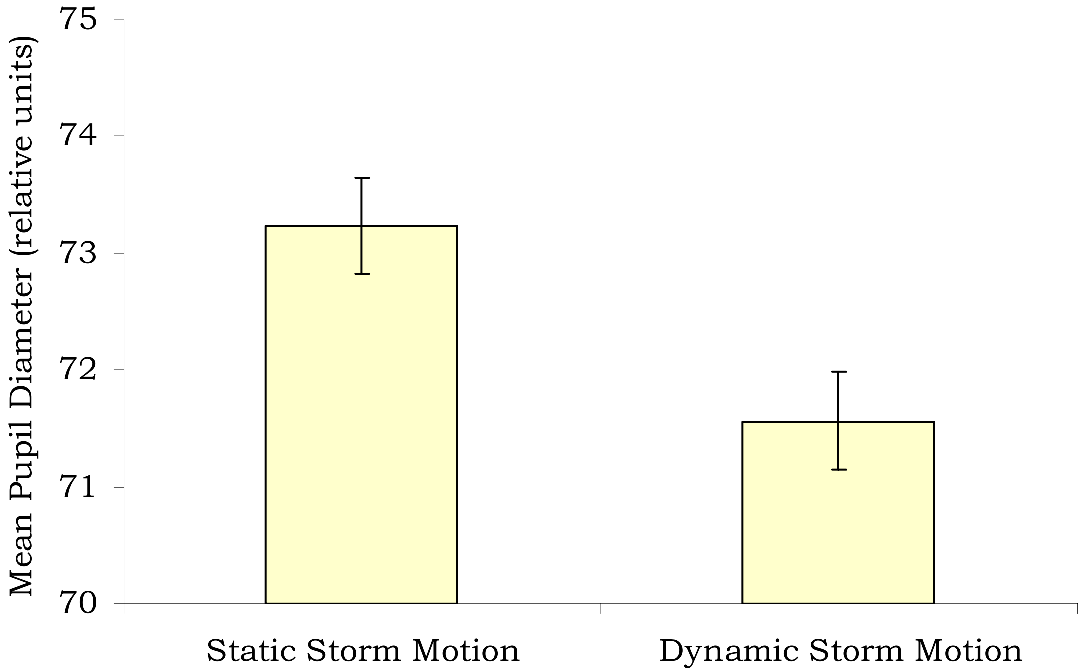

Figure 13. Mean pupil diameter (relative units) for the static and dynamic Storm Motion tools. The relative pupil diameter units can be converted metric units (mm) by multiplying the relative units by a scaling factor of .044. Error bars are 95% within-subject *CI*s.

3.4 Visual Areas of Interest

The purpose of the present analysis was to assess the fixation location and fixation duration while controllers were using the static Storm Motion tool. The static tool consisted of five spatially separated display features as shown in Figure 14 (left side). To evaluate this tool for tactical use, it is important to quantify what areas are of visual interest to controllers. Therefore, in the present analysis, we divided the tool feature area into separate AOIs to assess controllers' visual attention to different areas. The illustration in Figure 14 (right side) shows the static Storm Motion tool divided into three shaded areas. Area A covers the vector and speed numerals, B covers the area between the leading edge and the 10 minute extrapolated position, and C covers the area between the 10 and 20 minute extrapolated positions.

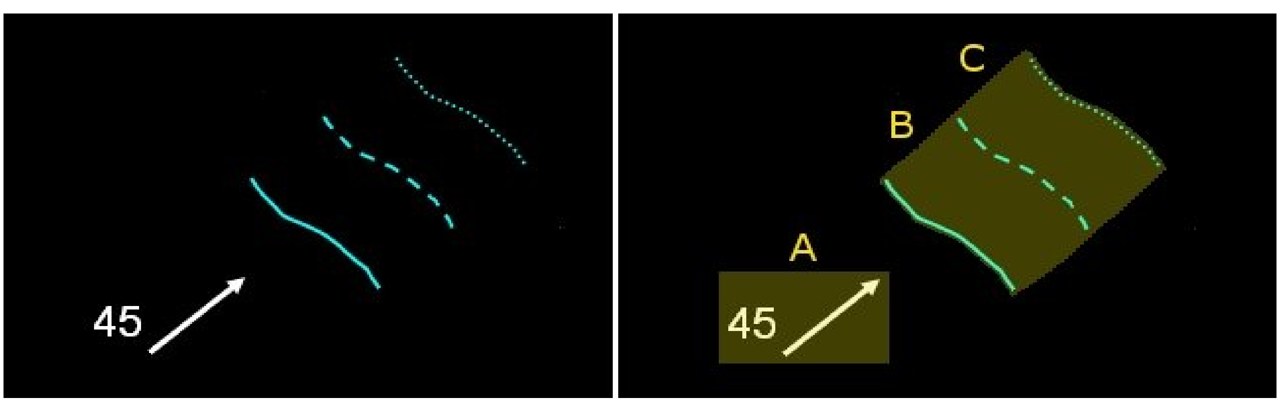

Figure 14. Static Storm Motion tool features (left) and fixation AOIs (right).

Figure 15. An example of static Storm Motion tool fixations. In this particular sample, nine fixations (yellow dots) are located in the area between the leading edge of the storm cell (solid blue line) and the 10 minute extrapolated position (broken blue line).

Figure 15 shows a data example of nine controller fixations (yellow dots) that are located within area B. For this analysis, we plotted all fixations that occurred while the static tool was activated (displayed). Figure 16 shows the mean number of fixations for the three AOIs. As can be seen in the figure, there were significantly more fixations in Area B compared to Areas A ($t(4) = 8.55$, $p < .001$) and C ($t(4) = 3.31$, $p = .015$), one-tailed tests with Bonferroni correction. However, as we can see in Figure 17, there were no significant differences in the mean fixation duration between these three AOIs.

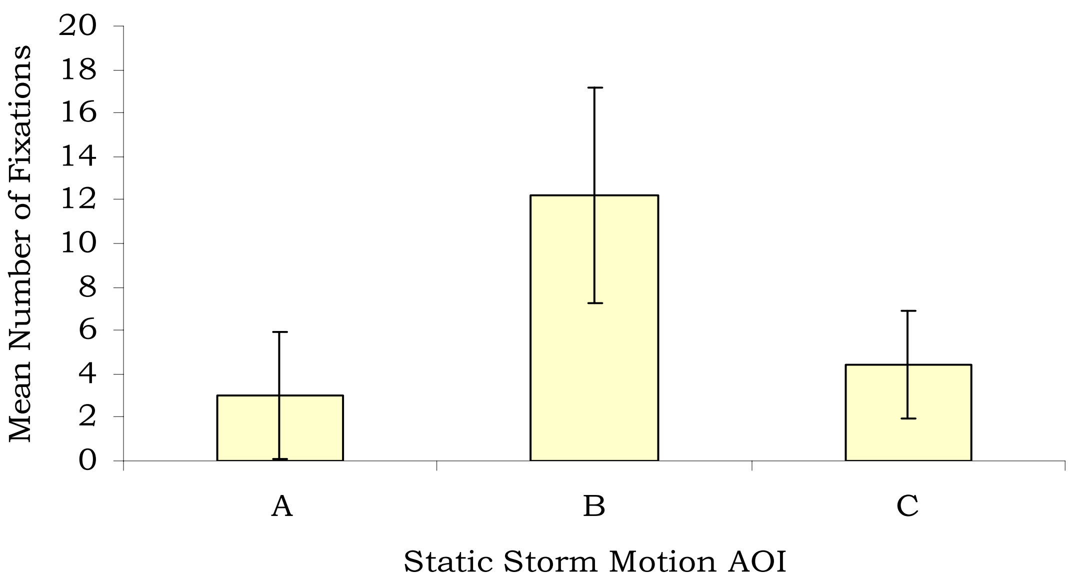

Figure 16. Mean number of fixations on static Storm Motion AOIs. Error bars are 95% within-subject CIs.

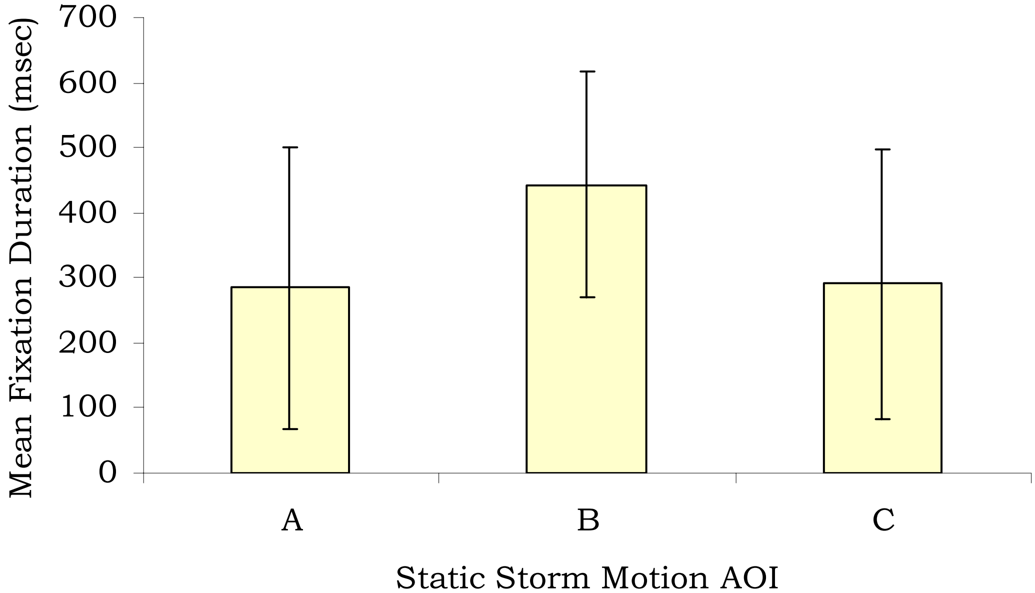

Figure 17. Mean fixation durations on Storm Motion tool areas A, B, and C. Error bars are 95% within-subjects *CI*s.

While controllers were viewing the static Storm Motion display, they focused their visual attention significantly more on the area between the leading edge and the 10 minute extrapolated position compared to other AOIs. However, there was no significant difference in the fixation duration between the three AOIs. This result is consistent with subjective feedback from controllers, where they stated that the 10 minute extrapolated position was most useful for severe weather avoidance during terminal ATC. It is also consistent with the size of the sector and traffic characteristics used during the simulation.

4. DISCUSSION

The attention capture phenomenon implies that some events penetrate our attention and interrupt scan path behavior even though they might be irrelevant to the task at hand. For example, the abrupt onset of a new display object as well as abrupt feature changes cause this phenomenon and it is especially strong when a stimulus is unique in both dimensions (von Mühlenen, Rempel, & Enns, 2005). In our static Storm Motion display, the activation caused tool features to appear on storm cells throughout the display. This abrupt onset captured controllers' attention and resulted in significantly larger scan path areas, scan path distances, and scan path durations compared to when controllers were using the dynamic tool. Therefore, rather than facilitating and enhancing controller scan path behavior, the static tool interrupted goal-directed exploration and produced less efficient scan path behavior. Furthermore, controllers had significantly larger pupil diameters when using static tools compared to dynamic tools, which is indicative of higher visual and cognitive workload (Van Orden, et al., 2001). Although we found negative costs from using the static Storm Motion tool, we want to mention available possibilities to improve our static tool and thereby enhance controller affordance-pickup during tactical use.

First, the static Storm Motion tool provides useful information about cell speed, motion direction, storm cell leading edge, and extrapolated positions. Specifically, we show that most fixations occur in the AOI between the leading edge and the 10 minute extrapolated position. This fixation behavior agrees with subjective feedback from controllers stating that they preferred the 10 minute extrapolated position. The focus on AOI area B (see Figure 14) is also consistent with the size of the generic sector and the time it takes arrivals to reach sector runways for landing. It is not likely that it is the lack of information that is the problem with the static tool; rather, it is the presentation format that is less favorable for tactical ATC operations. By displaying Storm Motion information dynamically, we significantly reduced controller scan path areas, scan path distances, and scan path durations compared to the static display (i.e., the dynamic Storm Motion display produces significantly less attentional capture). Furthermore, we also significantly reduced controllers' visual and mental workload during dynamic tool usage as indicated by the reduced pupil diameter.

Second, it is possible that the static tool may have less negative effect on scan path behavior if it is displayed in smaller areas on the situation display. For example, rather than displaying all available Storm Motion information on cells throughout the display, it should be possible to define and tailor the presentation of this information to cover smaller, but more relevant areas. In our simulation, controllers used the Storm Motion information for specific purposes like severe weather avoidance during timing of arrivals and for runway selection. By restricting the activation of Storm Motion information to predefined sector areas, we could limit the abrupt onset of display information across the entire display. This could potentially reduce the negative effect of attentional capture that occurred with the static tool during our simulation. Furthermore, the static tool features for wind direction and speed (Area A in Figure 14) and the 20 minute extrapolated position (Area C in Figure 14) seem to be of less importance during tactical tool usage. By only displaying elements that define the area between the storm cell leading edge and the 10 minute extrapolated position (Area B in Figure 14), it might be possible to enhance controller affordance pick-up during tactical operations even further while reducing attentional capture.

The negative effect of attentional capture is also evident from the almost complete lack of systematic controller scan path behaviors. Yang, Dempere-Marco, Hu, and Rowe (2002), discuss previous scan path research that found scans that often followed a regular path across an image, and that these patterns were often repeated and cyclic in nature. This is what we expected to find in our scan path data, a repeated cycle of scan paths that included various elements of the static display. We hypothesized that an influence on controllers by certain tool affordances would make them more likely to repeat these patterns during subsequent runs. However, our scan path analysis revealed an almost complete absence of such cyclic scan paths during static tool activations. Even more surprising, there was almost no repetition of any within-controller scan paths during the simulation. This result is at odds with previous scan path research that has demonstrated that although viewers exhibit differences in their scan path behavior, the scan paths are rarely random (Yang et al.).

We conclude, given what we know now, that animated storm predictions are more suitable for tactical ATC operations, as compared to static element-based representations. This does not mean that animations are always superior to static displays (see Lowe, 2003), but simply that the specific task context determines how well weather tools provide the intended affordances to viewers. Although both static and dynamic presentation modes provide affordances relevant for controllers during tactical operations, a potential consequence of element-based approaches is attentional capture. While this poses relatively little problems during strategic use of weather tools, during time-critical decision making in tactical ATC, it creates a conflict between the controllers' immediate task goals and the visual systems priority for novelty detection (von Mühlenen et al., 2005). If novelty is all that a weather tool provides, then viewers might fail to connect the novel information with the appropriate reference frames (e.g, aircraft, runways etc.). Consequently, the tool might fail to enhance effortless pickup of display affordances. Therefore, designers need to assess time-critical tasks for any interference of goal-directed scan behavior. As we have shown here for the case of severe weather avoidance, by animating storm cell extrapolations we greatly enhanced controller affordance pickup. This led to more efficient scan path behavior and reduced visual workload. By using this display principle when designing future information displays, we should be able to create weather tools that increase controller efficiency and safety during weather avoidance in tactical ATC.

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Acronymns

AOI	Areas-Of-Interest
ATC	Air Traffic Control
ATWIT	Air Traffic Workload Input Technique
CIWS	Corridor Integrated Weather System
ITWS	Integrated Terminal Weather System
POG	Point-Of-Gaze
STARS	Standard Terminal Automation Replacement System
TRACON	Terminal Radar Approach Control
WIDS	Weather Information Display System