Development of Advanced Terrain Awareness & Warning Display System

FINAL REPORT

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INFORMATIVE ABSTRACT

Controlled Flight into Terrain is one of the major sources of accidents in aviation today. Studies have shown that the use of Terrain Awareness and Warning Systems (TAWS) can decrease the number of such accidents. A problem with current TAWS is that the majority of them use the same display window as other information such as weather, traffic, airport positions, and moving map programs. The amount of clutter the terrain information alone adds to the displays makes the perception of other information difficult. This report discusses the design, development, and testing of a de-cluttered TAWS display where the traditional color-coded contour terrain is replaced with a single red contour indicating the projected points of impact of the aircraft; this red contour takes into account both the aircraft's current altitude and flight path angle. Although the red-contour terrain depiction covers less display area, it should still provide the same level of terrain awareness as the multi-colored design. A comparative testing of the red-contour and multi-colored TAWS was conducted using the basic flight displays in Microsoft Flightsim, along with other simulation software and equipment. Results show no significant difference in the performance of the 2 displays. However, since an un-realistic simulation element regarding changes in vertical speed of the aircraft greatly affected the performance of the red-contour, further studies with more sophisticated simulators may produce statistically significant results.

1. INTRODUCTION

1.1 BACKGROUND:

Ground Proximity Warning Systems (GPWS) have been in use since they were first introduced to the world of aviation in the 1970s. Before that period, pilots relied primarily on paper maps and out-of-window scenery for a sense of the terrain in the aircraft's immediate vicinity. Since the introduction of terrain alerting systems, not only have pilots had the addition of a third visual aid, but advancements leading to the current Enhanced GPWS (EGPWS) – also called the Terrain Awareness and Warning System (TAWS) – allow for more warning time to avoid impact with terrain. Unlike the GPWS, which is limited to look-down capability (i.e., it detects terrain below the aircraft[6]), the TAWS uses a look-ahead sensor, which predicts terrain ahead of the aircraft via information gathered from a regional terrain elevation database.[1] This alerting system has undergone further transformation into the Ground Collision Avoidance System (GCAS), which provides predictive warning (like the TAWS) while also supplying the pilot with information about evasive maneuvers.[6] However, the GCAS is primarily used in the Air Force rather than in commercial or general aviation.

One of the concerns with the existing TAWS is that it is mostly geared towards larger, commercial aircraft where such a system is required by regulation. The size and cost of these TAWS make it impractical for smaller, general aviation aircraft. The few designs that are available for general aviation have serious drawbacks: either the terrain information is so poorly displayed that it is of little help to the pilots, or the terrain information is so cluttered that it compromises the readability of other information in the display. In a world where 86% of all accidents occur with general aviation aircraft and 16% of fatalities in general aviation accidents are caused by CFIT,[1] it is imperative to develop a compact, affordable, and readable TAWS for general aviation use.

1.2 HYPOTHESIS

HYPOTHESIS: Reducing clutter in the terrain awareness and warning systems will improve overall readability of the display without having any adverse effects on the terrain awareness (i.e., number of false alarms and reaction time).

1.3 BRIEF OVERVIEW OF PREVIOUS WORK

Much work has been done over the past years in an attempt to improve the accuracy and clarity of the TAWS display. Research has ranged from adjusting the amount and type of data detail presented on the display screen to modifying the perspective in which the terrain is shown (i.e., 2-D, 3-D, perspective view, plan view, profile view, etc.) Work in the area of adjusting detail has shown disadvantages of using a monochromatic terrain display over the current multi-colored TAWS display, including a loss of necessary information for the pilot.[2] Meanwhile, research concerning the effect of terrain perspective on the pilot's recognition of danger has revealed interesting results. In particular, plan (bird's eye) and perspective (forward) views have been demonstrated to be the most preferred amongst pilots.[3]

Though much of this recent work concerns improving TAWS in commercial and military aviation, the world of general aviation is not entirely neglected. Aerospace companies, like Honeywell, have attempted to overcome the difficulties that arise with designing an inexpensive and compact display for general aviation pilots.[1]

1.4 BRIEF SUMMARY OF PROPOSED PROJECT

This project focuses on the use of TAWS in general aviation. The intent is to assess the effect that reducing clutter of the conventional design will have on the readability of the display. (This reduction in clutter is a particularly important aspect, because many of the TAWS that are available for general aviation squeeze the multi-colored design of display in commercial aircraft onto a smaller screen.) Furthermore, this project hopes determine that removing this clutter will not detract the pilot from information he or she needs to avoid imminent terrain danger. Thus, the project’s significance stems from the implications its results will have for the use of TAWS in the world of general aviation.

2. OBJECTIVE AND SUCCESS CRITERION

OBJECTIVE: Use computer simulation to measure and compare pilot's performance with baseline and with a reduced clutter design.

SUCCESS CRITERION: Obtain data to determine whether the performance of the reduced clutter design is 1) better than the baseline's, 2) worse than the baseline's, or 3) indeterminate in relation to the baseline's performance due to a lack of statistical significance in the level of difference.

3. LITERATURE REVIEW

A review of literature shows that much research concerning TAWS has been done in the recent years. Such work primarily concerns the effect of certain parameters – e.g., the predictive capability of TAWS, the display design, etc. – on the discernment of terrain hazards (or, terrain awareness). Though the impact of screen clutter on terrain awareness has been mentioned, it has not been extensively studied. Thus, this review of literature includes studies that are not directly related to this project’s hypothesis but that may provide valuable guidance to the development of this experiment in terms of methodology and background information.

Since the introduction of TAWS in the late 1990s, many researchers have questioned the effect of the advanced warning time provided by look-ahead altimeters (which, as described earlier, replace the look-down sensors of the GPWS) on the pilot’s awareness of terrain hazard. A thorough study presented by de Muynck and Khatwa[4], concludes that “predictive terrain alerting” results in no obvious improvement in terrain situational awareness. This conclusion is confirmed by Moroze and Snow, who note that though TAWS provides more warning time, it does not give the pilot a better understanding of the emergency situation in which he is placed (i.e., situation awareness).[1] However, other sources indicate the complete opposite – an apparent improvement in situational awareness.[2, 5] One of the conflicting sources, Sachs and Sperl's "Experimental Low Cost 3D-Display for General Aviation Aircraft," concludes that terrain displays with predictive capability "enhance the control performance of the pilot and reduce his workload," thus allowing the pilot to pay greater attention to his surroundings.[5] Though this discrepancy between conclusions exists, it does not significantly impact this project since its major focus is on the readability of the display (i.e., screen clutter) – and not predictive versus immediate alerting.

In recent years, researchers have also addressed the effect of display design on the pilot's terrain awareness; many argue that terrain awareness can be improved or reduced depending on how the information is displayed. Glover,[2] as well as Wickens[6] and de Muynck,[4] all conclude that pilots tend to prefer (and react more readily to) red and/or yellow because such colors are intuitively associated with danger or caution. Thus, it is no surprise that the majority of TAWS use colors (as well as green) to symbolize areas of hazardous terrain. However, the conclusion is not as clear in terms of the effects of 3D versus 2D displays, and within the latter class, plan view (i.e., bird's eye view), side (profile) view, and forward (perspective) view of terrain information. Glover does present the point that "engineering limitations and economic necessities" constrain the evolution of TAWS, noting that most displays are plan view for the sake of compatibility with the rest of the flight deck plan-oriented display hardware.[2] Thus, these general display design choices reinforce certain aspects of the red contour design (which consists of a red line indicating points of impact in a plan view format) but does not imply a halt in the evolution in TAWS design. Other aspects of his study, such as testing methods and the error challenges faced, are similar to what will occur in this experiment.

Though this literature review has revealed extensive work in TAWS research, little has been undertaken in the area of clutter reduction. While researchers have acknowledged the possible effect of clutter on readability of information (other than terrain) presented by the display, this 16.62X project will be one of a few to analyze the question in detail.

4. DESCRIPTION OF EXPERIMENT

4.1 OVERVIEW OF EXPERIMENT & PROTOCOL

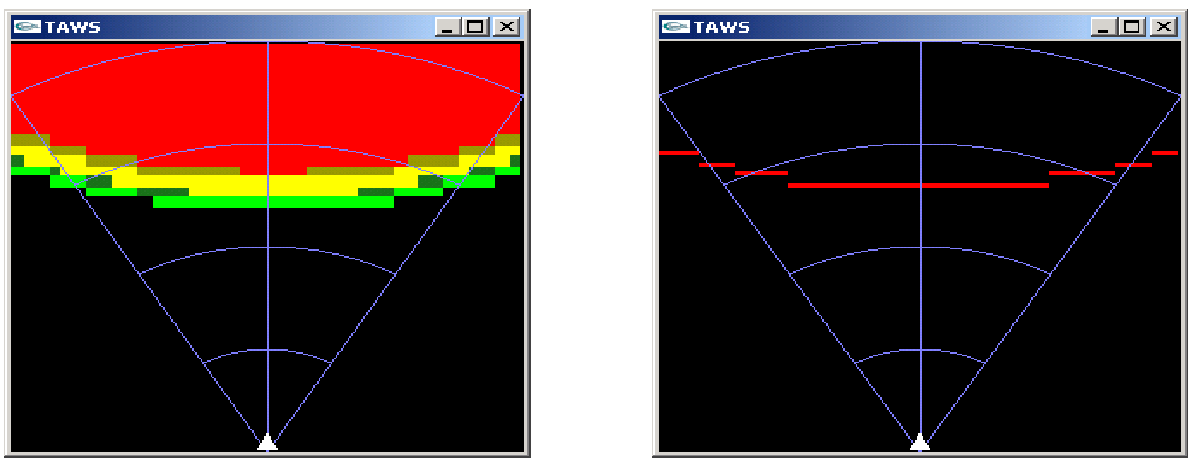
In this experiment, a total of 12 subjects were instructed to complete 8 scenarios of a computer-simulated flight. Approximately half of the subjects were tested with the baseline display first and the red contour second, while the other half followed the reverse order. (Details as to this test setup are explained in the Error Mitigation section.) The primary task of the subjects was to follow a given flight course while pressing a red button when hazardous terrain was perceived, thus ending the simulation. Meanwhile, the secondary task was to identify air traffic (i.e., popups) by pressing the corresponding key on the keyboard. (Subjects were also asked to detect popups that were within 1,000 feet of the aircraft's altitude by pressing the space bar.) All subjects were instructed to treat the primary task with higher priority and handle the secondary task with lesser importance. Experimental data was gathered to measure popup recognition and terrain awareness while pre- and post-experiment surveys were used to obtain background and subjective data. All subjects were to complete a test flight simulation without a TAWS display and a practice flight scenario with either the baseline or red contour display before they started the actual simulation with that display design.

4.2 DESCRIPTION OF TEST ARTICLES AND SUBJECTS

The test articles in this project include two computer-simulated TAWS displays – 1) the baseline design and 2) the red contour design.

The *baseline design* is the conventional multi-colored display used by most commercial aviation pilots, and recently redesigned by Honeywell as a compact unit for use by general aviation pilots (see Figure 2a). This display uses six colors to represent different terrain elevations with respect to the aircraft's current altitude. (The terrain color breakdown is as follows: red = terrain 2000+ feet above the aircraft, dark yellow = terrain between 1000 and 2000 feet above the aircraft, yellow = terrain between 500 feet below the aircraft and 1000 feet above the aircraft, dark green = terrain between 1000 and 500 feet below the aircraft, and green = terrain 2000- below the aircraft.)

Meanwhile, the *red contour design* is a reduced-cluttered design, which replaces the red/yellow/green terrain regions of the conventional display with a single red contour representing points of impacts (see Figure 2b). These points of impact are based on calculations of the aircraft's flight path angle.



(a) **(b)**

Figure 1. Red Contour Display and Baseline Display

Both displays are in a plan (bird's eye) view format lines which are 30-degrees apart and arcs which are 2 nautical miles apart. The time to impact (in seconds) which will appear in bottom right corner in white if the pilot is within X seconds upon crashing and flash in red if under 60 seconds (not shown). The aircraft is represented by a white triangle in the bottom middle of the screen.

The test subjects in this experiment are limited to those who have logged actual piloting hours or, at a minimum, had prior Microsoft Flight Simulator experience. These restrictions are placed to reduce the amount of time needed to train/update all subjects on the flight simulation program.

4.3 DESCRIPTION OF SCENARIO DESIGN

The scenarios used in this experiment were designed to reflect real flight situations. All scenarios were flown using Microsoft Flight Simulator's Cessna SP172 Skyhawk (which is a common general aviation aircraft) under almost zero visibility to reduce the out-of-window view. Each scenario started at a cruising altitude and speed of 9,000 feet and 124 mph, respectively. Subjects received instructions to descend to 8,000 feet by the first waypoint, maintain the specified elevation until the second waypoint, and turn to a heading of 030 at the second waypoint. The average flight time for each scenario was 5 minutes, ending when subjects crashed, pressed the red button upon detecting a hazard, or were terminated by the investigator. (The investigator terminated a scenario when it ran its time limit.) The four scenarios are described in Table 1.

Table 1: Scenario Design

Scenario Number	**Scenario Name**	**Description**
1	NO HAZARD	non-hazardous terrain presented on given flight course
2	REAL HAZARD	terrain hazard presented between first and second marker (before turning to 030 heading)
3	FALSE HAZARD	terrain hazard presented off of given flight course
4	TURN INTO HAZARD	terrain hazard presented after turn to 030 heading

In addition to terrain hazards, popups appeared within each scenario approximately every 3.5 seconds to create a secondary task for the subjects (see Figure 2). Each popup consisted of one of four letters (A, B, C, and D), a circle, and an absolute altitude ranging between 6,000 and 10,000 feet.   Subjects were instructed to press the key on the keyboard corresponding to the letter accompanying a popup. They were also instructed to press the space bar for popups which were at altitudes within 1000 feet of the aircraft.

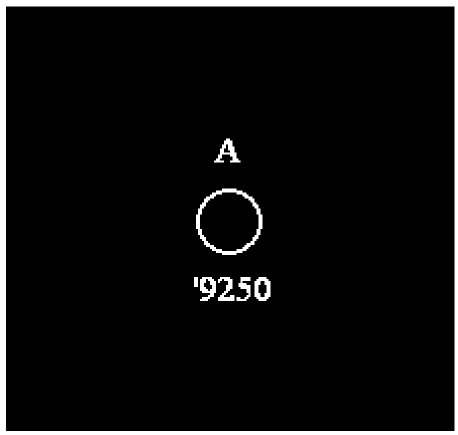


Figure 2. Popup (Not the actual size)

Before the scenarios were run, each subject underwent: 1) a flight simulation without a TAWS display, 2) a test hazardous scenario with the baseline display before the actual baseline simulation, and 3) a test hazardous scenario with the red contour display before the actual red contour simulation. In all three cases, subjects were instructed to adhere to the given flight course and allowed to begin the simulation after doing so. (The first simulation allowed the subject to adjust to Microsoft Flight Simulator while the latter two scenarios allowed the subject to become familiar with the TAWS display design.)

4.4 DESCRIPTION OF THE APPARATUS SETUP

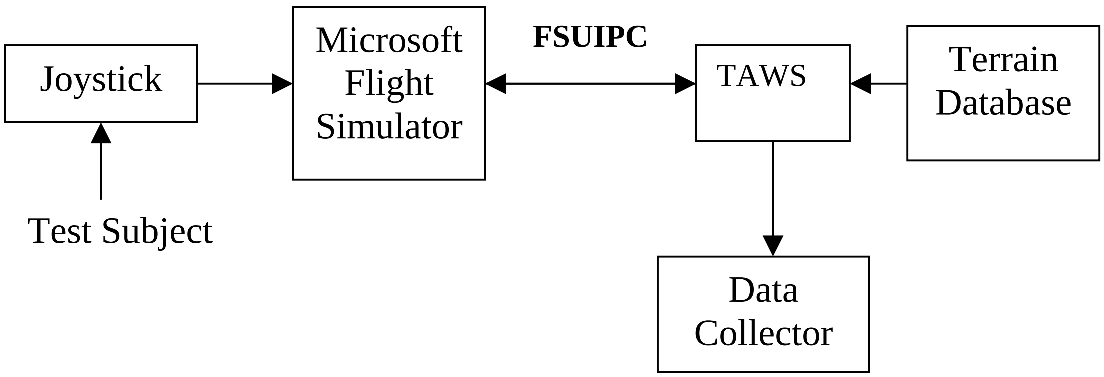


Figure 3. Schematic of Apparatus

The apparatus used in this experiment is depicted in Figure 3. The Cessna cockpit panel and out-of-window view (night sky) were displayed on a computer monitor using the Microsoft Flight Simulator program. A joystick was attached to the computer allowing the subject to maneuver the simulated aircraft. A 400x400 (baseline/red contour) pixel TAWS display window was created using OpenGL and appeared next to the Microsoft Flight Simulator cockpit on the same computer screen. Data was exchanged between the simulator and the TAWS via a Flight Simulator Unit Inter-Process Communication (FSUIPC) link. A program called Terraform was used to create an artificial terrain database which fed terrain position (in x, y) and altitude (z) into the TAWS for display. Finally, a Data Collector was coded in the C programming language to collect aircraft and terrain position, velocity, and keyboard inputs/button presses. This data was used for calculations of reaction time and other variables.

4.5 SCOPE OF TESTS

A total of 12 subjects were obtained from MIT's Department of Aeronautics and Astronautics, including undergraduates, graduates, and members of staff. Approximately half of these subjects started the computer simulation experiment with the baseline display while the remaining half started with the red contour. Preliminary data was obtained from 4 of the 12 subjects, and one subject was thrown out because of personal time constraints, which did not allow for proper adherence to the test protocol. Each simulation lasted an average of 1½ hours, while each scenario lasted an average of 5 minutes. The experiment was conducted at the MIT Gelb Lab and spanned two weeks.

4.6 ERROR MITIGATION

The following errors were anticipated and mitigated so as to not affect the results of the experiment.

- ***Subject variability*** – i.e., the fact that each subject is unique and thus reacts at a different speed compared to other subjects – was considered. In order to mitigate this source of error, the mean of the reaction times of all ten subjects was analyzed. Thus, though one subject may be faster than another one in responding to a terrain hazard, if both subjects show improved performance between displays, the mean will demonstrate this.

- ***Fatigue*** is another possible source of error and may occur in two forms.
    1) Fatigue may reveal itself as the simulation progresses and the subject's reaction time begins to decrease, thus negatively influencing the data. This source of error was mitigated by switching the order in which the display designs were tested (i.e., counterbalancing the order); the subjects were divided into 2 groups, one group using the baseline display first and the other using the reduced clutter design first. The scenarios were also counterbalanced between display designs and subjects. In addition, the experiment itself was designed so as to be as short as possible to minimize fatigue. There was also an option for a short break between the switching of TAWS displays.

2) Fatigue may also manifest itself if the subject comes into the experiment having not had sufficient rest the night before simulation day. This was mitigated by reminding subjects ahead of time of the importance of a good night's rest.

- ***Learning effect*** (i.e., getting better as the experiment progresses) was another possible source of error in this experiment, which may manifest itself in an improvement of reaction times. The displays and scenarios were counterbalanced (as in the Fatigue case) to mitigate this possible source of error, and training time was provided to ensure that the subject was familiar with the display and procedure before the actual experiment.

4.7 <u>TEST MATRIX</u>

The independent variables in this experiment are the two display designs (baseline and red contour) and the four scenarios, thus resulting in a two-dimensional test matrix (see Figure 4).

The dependent variables in this experiment consisted of reaction times to terrain hazards and popups, percentage of popups recognized (and falsely detected), number of hazards recognized (and falsely detected), and post-simulation survey ratings. These dependent variables were either used to evaluate terrain awareness or to measure the readability of the display.

The parameters in this experiment are the test subjects. (The subjects were not considered as independent variables in order to decrease the scope and complexity of the project.)

DISPLAY DESIGN / SCENARIO	**Red Contour**	**Baseline**
1		
2		
3		
4		

Figure 4. Test Matrix

5. RESULTS

In an attempt to evaluate overall readability of the display and terrain awareness, experimental data was gathered to measure popup and terrain hazard recognition. Subjective data to supplement these results was also gathered using post-experiment surveys. Of the 12 subjects tested, 6 had a minimum of 80 flight hours logged and 6 had at least 10 hours of Microsoft Flight Simulator experience. Seven subjects had never used a TAWS display prior to the experiment.

5.1 OBJECTIVE DATA

The following results show the experimental data obtained from the 7 actual subjects. (As previously stated, 4 of the 12 subjects were used to obtain preliminary data and one was thrown out due to personal time constraints that disallowed a proper adherence to the test protocol.)

5.11 Popup Recognition

5.111 Reaction Time to Popups

A 2-tailed paired t-Test was done to determine if the type of TAWS display had an effect on the subject's average reaction time to popups. For this experiment, a statistical significance of 5% or less indicated that the display design had a significant effect. The resulting significance level of the popup reaction time was 8.95%, which showed no statistical significance.

For visual comparison, a graph was also plotted showing display design versus each subject's average reaction time to popups with both displays. Each error bar was created using the mean of the average reaction times for the 7 subjects and one standard deviation above and below the mean. The error bars also contain seven dots indicating the individual average reaction times of the 7 subjects with that display.

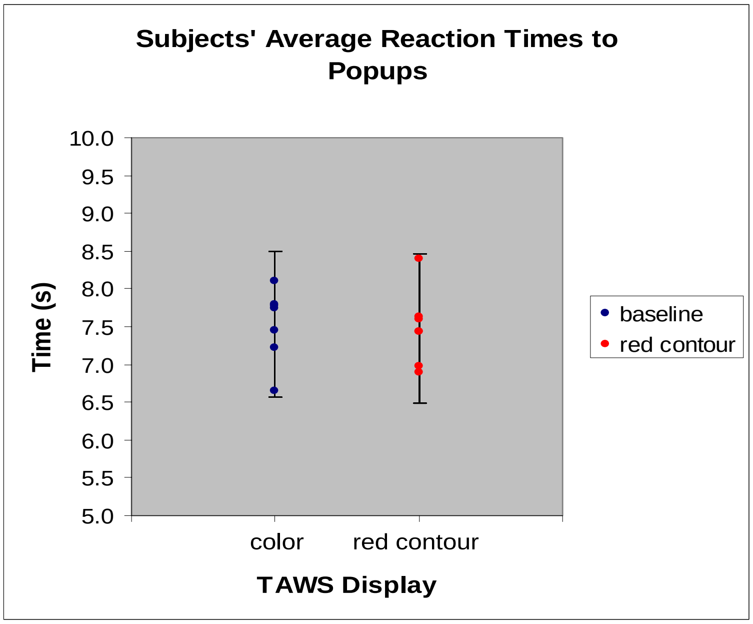
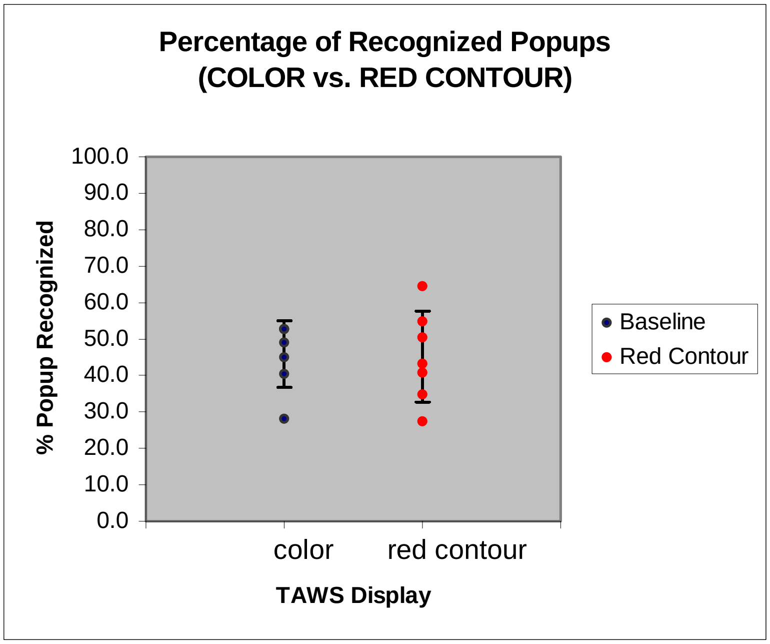


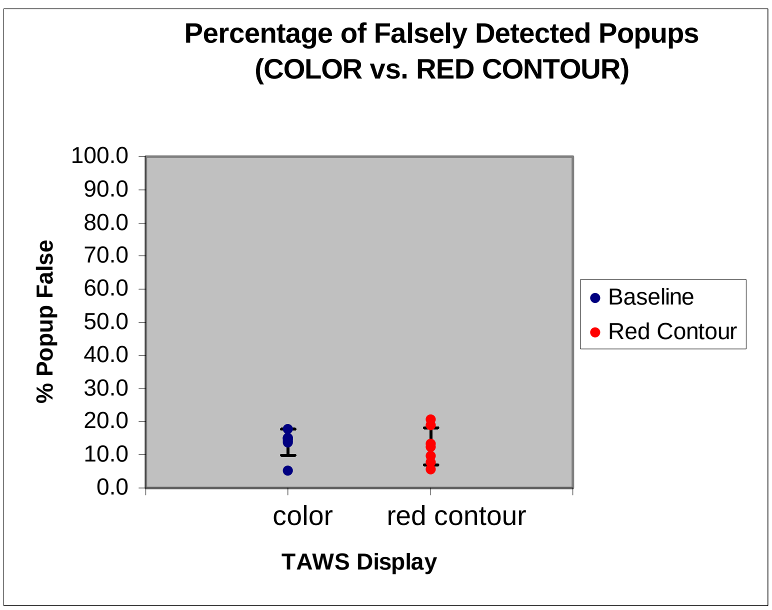
Figure 5. Subjects' Average Reaction Times to Popups

5.112 Percentage Popups Recognized (& Falsely Detected)

The results in Figures 7a and 7b show the percentage of popups recognized and falsely detected, respectively. The percentage of popups recognized consists of all popups which were detected (correctly and incorrectly) by the subject over all scenarios. The percentage of falsely detected popups consists of those popups which were incorrectly identified (for e.g., the subject pressed "A" for a popup with the letter "C").



(a)



(b)

Figure 6 Popup Recognition.

The figures above are plots of (a) the percentage of total popups recognized (i.e., incorrectly and correctly) and (b) the percentage of popups falsely detected.

5.12 Terrain Awareness

5.121 Reaction Time to Terrain Hazards

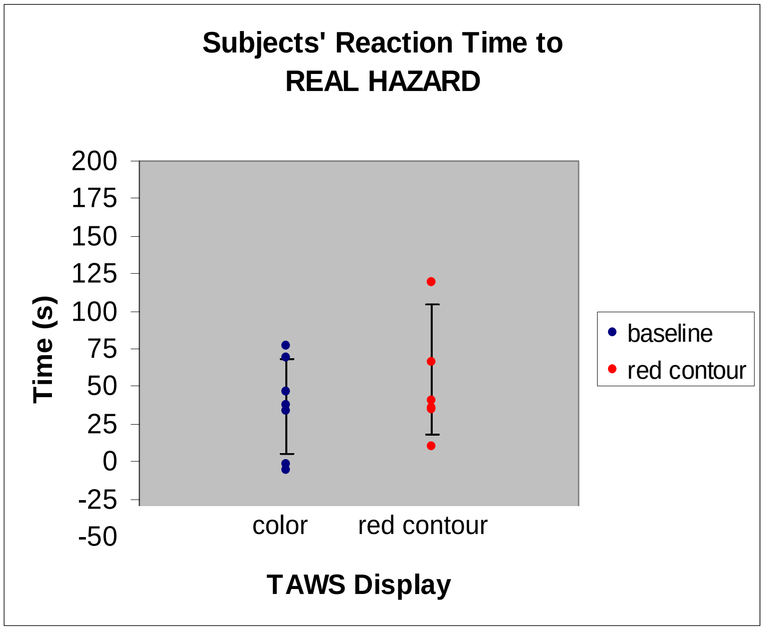
Two paired t-Tests (2-tailed) were done to determine if the type of TAWS display had an effect on the subject's reaction time to hazardous terrain. Again, a statistical significance of 5% or less indicated that the display design had such an effect. As shown in the table, neither of the two scenarios showed a statistical significance.

Table 2. Paired T-Test for Reaction Time to Hazards

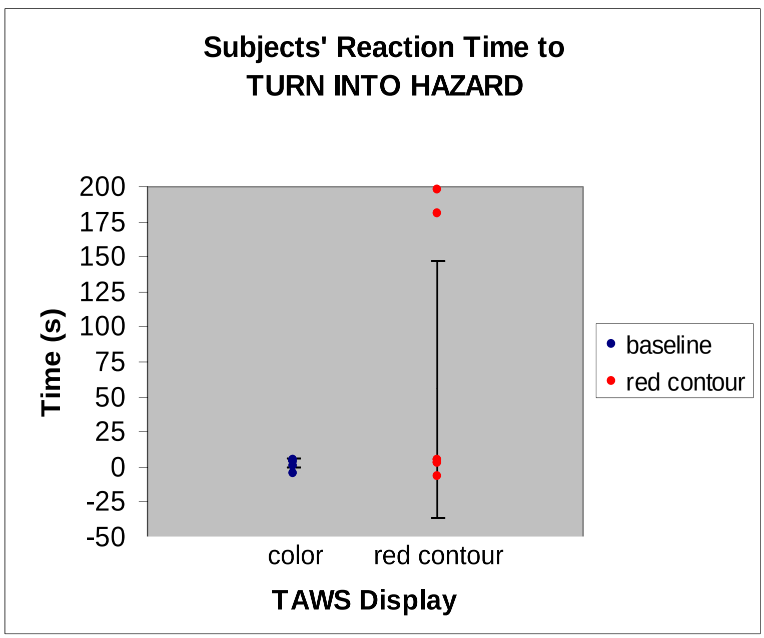
Statistical Significance

SCENARIO	SIGNIFICANCE
real hazard	0.326
turn into hazard	0.176

For visual comparison, two graphs were also plotted showing display design versus each subject's reaction time in both the REAL HAZARD and TURN INTO HAZARD scenarios. Each error bar was created using the mean reaction time of the 7 subjects and one standard deviation above and below the mean. The error bars also contain seven dots indicating the individual reaction times of the 7 subjects with that display. (Negative times were the result of a subject either crashing into terrain or flying significantly off course thus maneuvering past the hazardous terrain.)



(a)



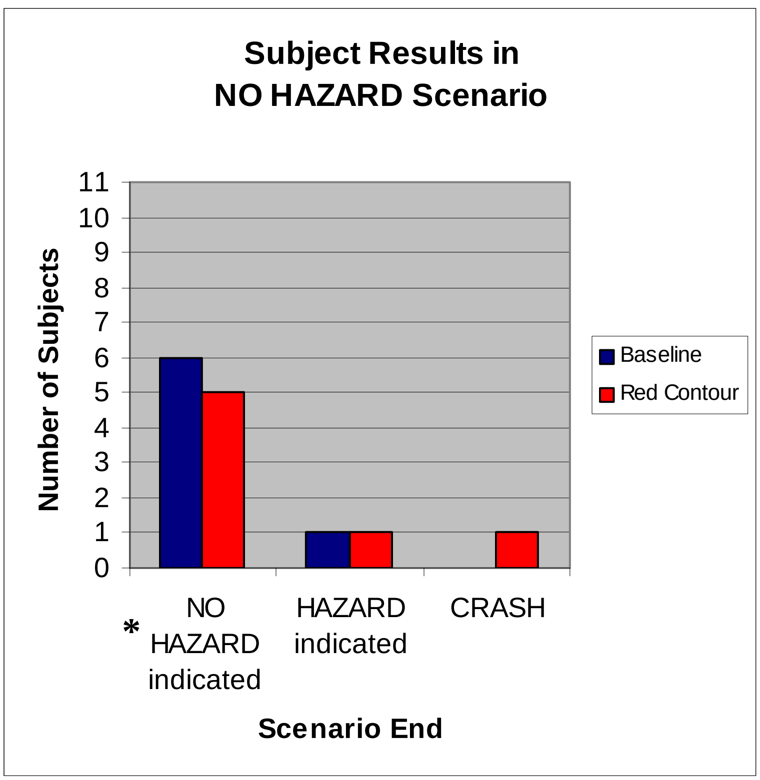
(b)

Figure 8 Reaction Time to Hazards.

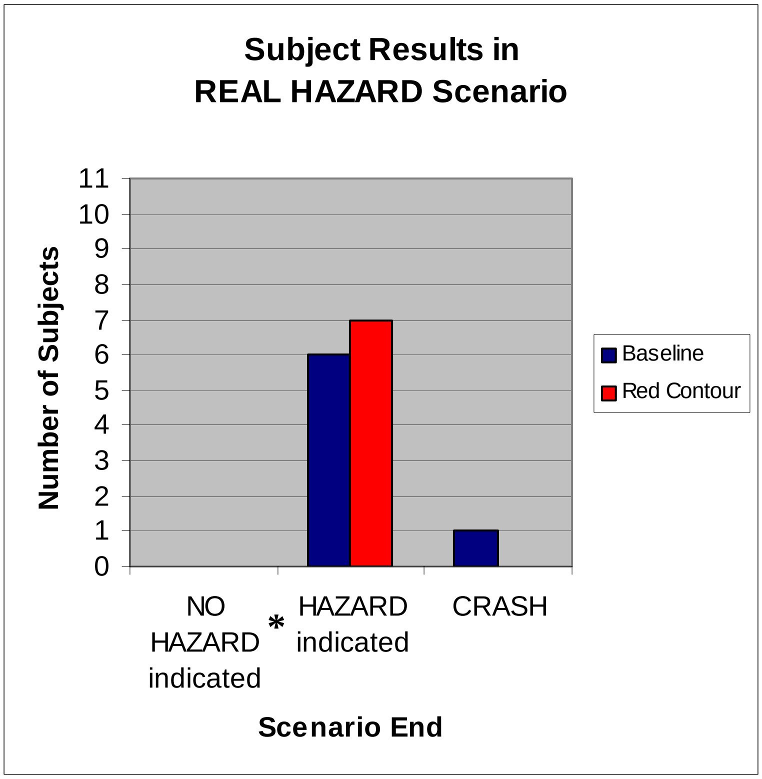
(a) Subjects' Reaction Times in REAL HAZARD and (b) Subjects' Reaction Times in TURN INTO HAZARD

5.122 Number of Terrain Hazards Recognized (& Falsely Detected)

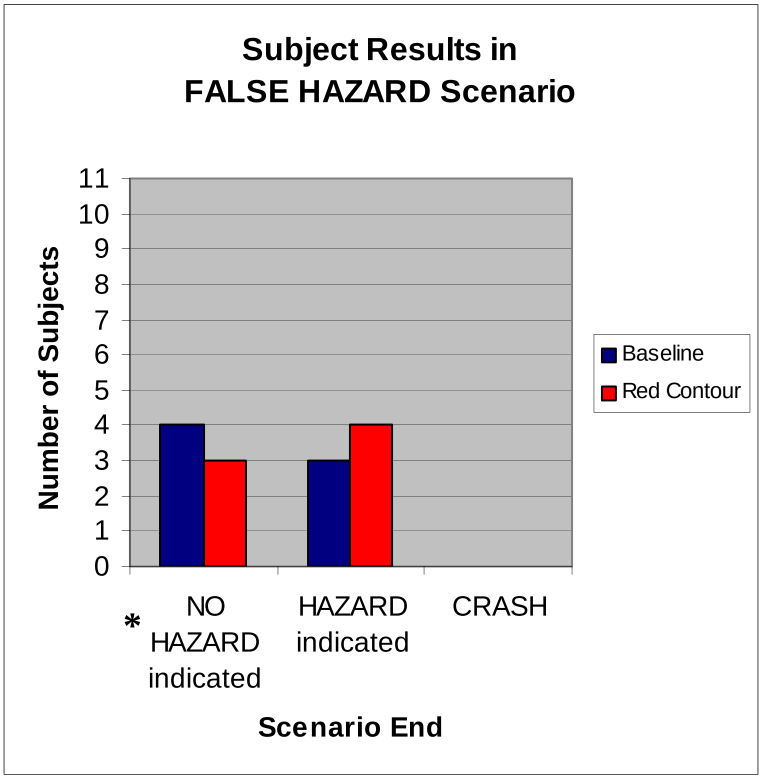
The results in Figures 9a through 9b show the number of subjects that either indicated a hazard, indicated no hazard, or crashed into hazardous terrain for each of the four scenarios and with both display designs. An asterisk preceding a "HAZARD INDICATED" or "NO HAZARD INDICATED" represents what the response should have been (i.e., the correct response) for that scenario.



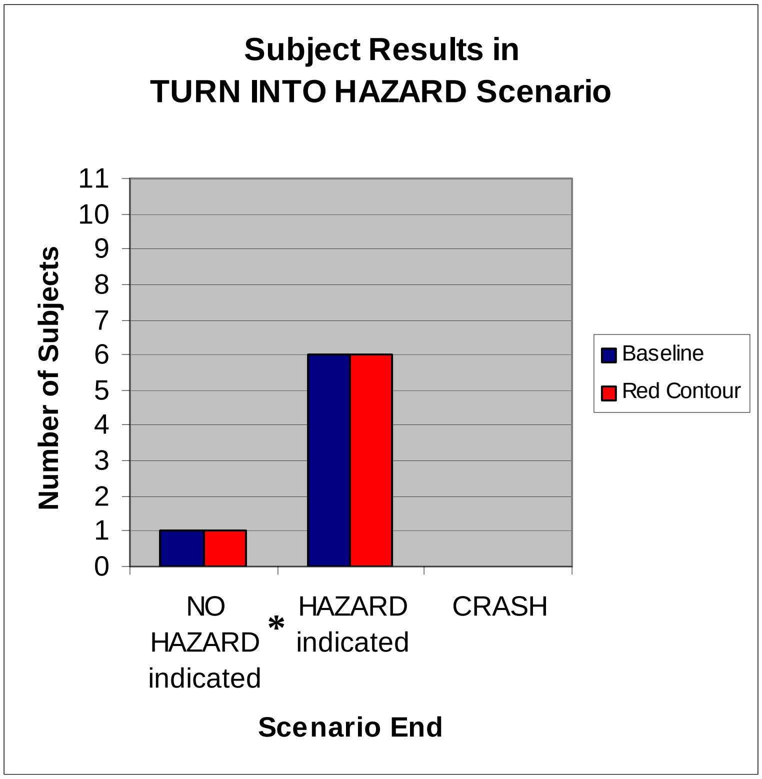
(a)


Subject Results in
REAL HAZARD Scenario
Number of Subjects
11
10
9
8
7
6
5
4
3
2
1
0
NO HAZARD indicated
*
HAZARD indicated
CRASH
Scenario End
Baseline
Red Contour

(b)


Subject Results in
FALSE HAZARD Scenario
Number of Subjects
11
10
9
8
7
6
5
4
3
2
1
0
*
NO HAZARD indicated
HAZARD indicated
CRASH
Scenario End
Baseline
Red Contour

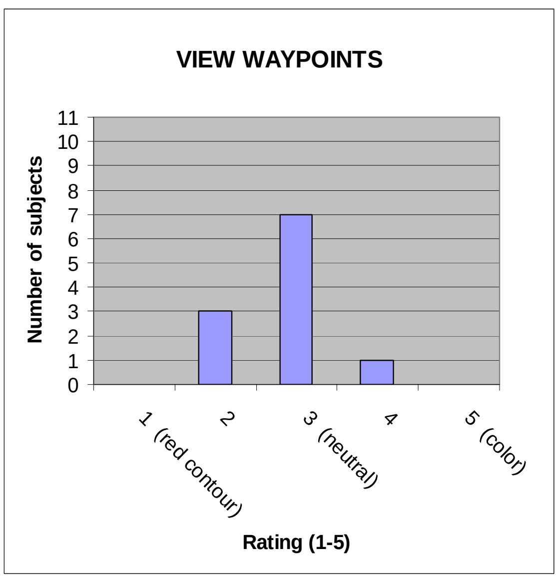
(c)


Subject Results in
TURN INTO HAZARD Scenario
Number of Subjects
11
10
9
8
7
6
5
4
3
2
1
0
NO HAZARD indicated
*
HAZARD indicated
CRASH
Scenario End
Baseline
Red Contour

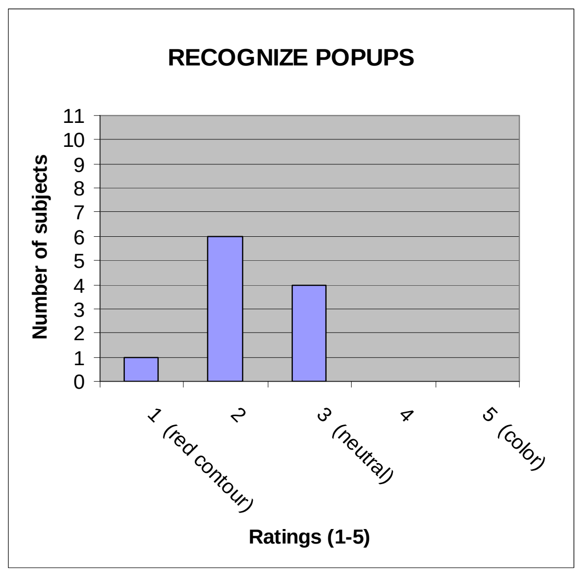
(d)

5.2 SUBJECTIVE DATA

The results in Figures 5a and 5b show the display design preferences for five performance categories. These results were obtained by plotting the display preference indicated for a post-experiment survey question against the number of subjects who indicated that preference. The survey was presented using a 1 to 5 rating scale: 1 representing a preference for the red contour, 3 representing neutrality, and 5 representing a preference for the baseline design. Only 11 of the 12 subjects were presented with the post-experiment survey because these subjects completed all 8 scenarios.



(a)



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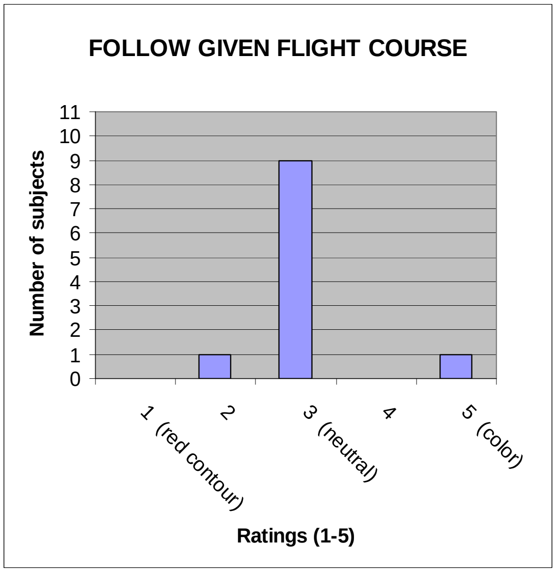
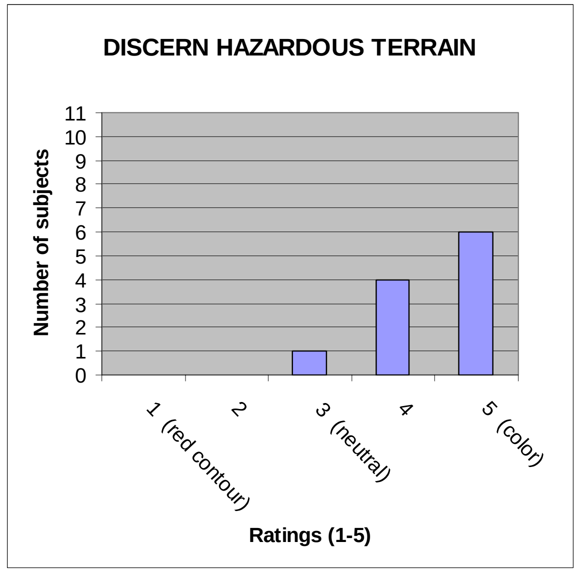
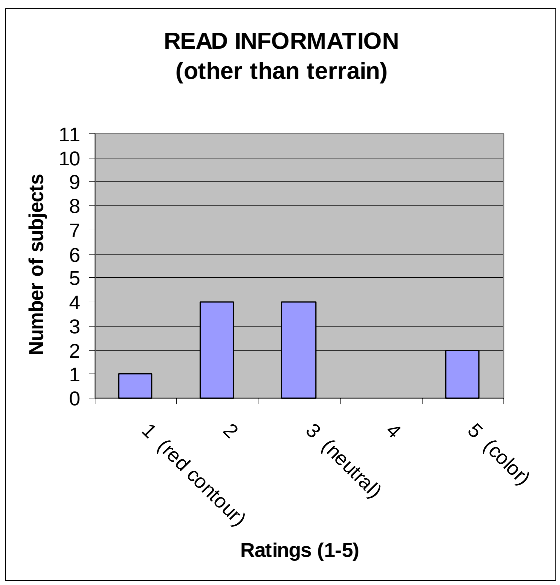


(c)



(d)



(e)

Figure 7. Subjective Ratings.

The figures above show the subjective ratings for the following post-experiment survey questions – "Which display provided you with BETTER ABILITY to": (a) view waypoints, (b) recognize popups, (c) follow the given flight course, (d) discern hazardous terrain, and (e) read information other than terrain/popups.

At the end of the post-experiment survey, 9 subjects commented that the baseline was the more preferred display overall because it presented more information about the terrain hazard.

6. DISCUSSION

6.1 OBJECTIVE DATA

6.21 Popup Recognition

For Figures 6, 7a, and 7b, the error bars for the multi-colored terrain and red-contour overlap each other, indicating that there's no statistically significant difference in the data. However, this does not mean that there is no difference in the performance of the 2 displays with respect to popup recognition; only the difference, if any, is smaller than the errors present in this experiment. Major error sources that may have led to these results are discussed section 6.3.

Note that in Figure 7a, number of pop-ups correctly recognized by the subjects generally falls between 20 and 70 percent. There are no percentages near 0 or 100. These results indicate that the workloads of the primary and secondary tasks are properly adjusted to allow for a range of performances. (The secondary task can be used to assess both the readability of the displays and the difficulty of the primary task. If the terrain scenarios were too difficult to handle on its own, then subjects would not have the time to recognize the pop-ups, regardless of the display readability. On the other hand, if the workload was so light that all subjects recognized 100% of the pop-ups correctly, then the popup task would not have provided a good indication on the difference in usability of the 2 display formats.)

6.22 Terrain Awareness

There is not only no statistically significant difference in the reaction time to terrain recognition for the 2 displays, the error bars on the results for these displays highly overlap each other, indicating that the performance with the displays are comparable. One point to note is that for the turning into hazard scenario, the error bar for the red-contour display is much larger than that of the baseline display. This is due to the fact that 2 of the subjects recognized the terrain hazard well before the turn, leaving them with very large time to impacts at the time of recognition. We do not have enough evidence to decide the cause of these results: the red-contour may be better for recognition of hazard off of the current heading, or it might be simple coincidence that both recognition of hazards before turning happened with the red-contour display.

The plots for the number of crashes, hazard recognitions, and no hazard recognitions once again indicate a closeness in the performance of the 2 display with respect to terrain recognition. There is a very small amount of variability in the subjects' performance across the displays: for most cases, the number of subjects under each column differs by no more than 1.

For most scenarios, the majority of the subjects correctly identified the nature of the terrain: hazardous or non-hazardous. For the No Hazard scenario, there is no terrain on the given path. Therefore, the subjects should have flown safely through the scenario without indicating a hazard: 6 out of 7 subjects for the multi-colored and 5 out of 7 for the red-contour did this. The Real Hazard and Turning into Hazard scenarios have terrain hazards on the given path. Thus the subjects should have pressed the terrain hazard button, and most subjects did this. The major exception to proper terrain recognition is the False Hazard scenario. There is no hazard on the given course, yet for each display, about half of the subjects noted terrain hazard. The False Hazard scenario has a major terrain hazard along the initial heading of the aircraft. The hazard is right past the heading change marker (marker 2); thus if the subjects executed the course precisely, s/he would not run into terrain. However, the terrain is very close to the course; and post scenario questioning revealed that most subjects who noted hazard for this case did so because they believed that the terrain would present a problem after the aircraft performs the turn.

However, it is important to note that although there is a large amount of false terrain recognition for the False Hazard scenario, the level of misinterpretation is the same for the 2 displays. For each case, the subject was presented with the same terrain under 2 different display formats. Thus the difficulty level is the same across the 2 displays and will not affect the result of this comparative study.

6.2 SUBJECTIVE DATA

In the subjective results, the subjects favor the multi-colored display for terrain hazard recognition and the red-contour display for the ability to recognize pop-ups (Figure 5). For the other 3 questions (ability to view waypoints, follow flight course, and read other information), subjects did not show any clear preference towards one display or the other.

These findings seem at odds with the objective data, where there is no clear indication of difference in the displays' performance. The reason behind these results is unclear. It is possible that the subjects' perception of performance simply do not agree with their actual performance. Or there could be actual differences in the displays' performances buried by the errors.

6.3 Errors

Red contour instability and unbalanced learning effect are two sources of error that may have given one display an advantage over the other. Other errors such as subject variability, fatigue, etc. still add noise to the data; however, there should have been similar effects on the two displays.

6.3.1 Red-contour Instability

The major source of error in this experiment comes from a lack of realism in the flight simulation: the vertical speed of the simulation aircraft is very difficult to control. This may either be caused by over sensitivity in the joystick or unnatural depiction of aircraft behavior within MSFS. Whatever the cause may be, its effects are substantial. Unstable vertical speed makes the altitude difficult to maintain, which increases the workload of the subject. Although performance under both displays is affected to an certain extent, the effect on the red-contour display is much more dramatic due to the fact that the red contour depends not only on the altitude but also on the flight path angel (FPA) of the aircraft, which is directly related to the vertical speed. When the vertical speed changes rapidly from –20 knots to +20 knots and beyond, the red contour also wildly moves across the display. This not only distracts the subjects, but also makes terrain hazards difficult to determine.

There is one other subtle but significant effect of this unstable vertical speed. In the case of the red-contour display, the subjects must put forth great effort into the control of the vertical speed in order to discern hazard in the scenario. This greatly increases the primary workload for the red-contour scenarios over that of the multi-colored scenarios. This increase in workload very likely affected the subjects' performance on the secondary task, the popup recognition. In fact, one subject commented after the experiment that s/he could not pay as much attention to the pop-ups because the red contour was so difficult to control. There is not enough data to draw solid conclusions to this claim. However, the red-contour display did show performance comparable to the multi-colored display even under such conditions. Therefore, it is not unreasonable to believe that testing under more realistic simulation environments could result in significantly higher performance for the red-contour display.

6.3.2 Learning Effect

After the removal of subject 10, we were left with objective data from 7 subjects. 4 of these subjects were tested first with baseline and then the red-contour display, while the other 3 were tested in reverse. This created a slight imbalance in the mitigation of the learning effect. However, since the number of subjects beginning with each display differs only by 1, the offset should not be great. Also, we did not notice any dramatic improvement on subjects' performance towards the latter half of the testing sessions; thus we are not very concerned about this source of error.

7. SUMMARY AND CONCLUSIONS

Summary of results (and discussion of results):

- *Subjective ratings:* These results determined that subjects preferred the baseline display in recognizing terrain hazards and the red contour design in recognizing popups.

- *Percentage of popups recognized (& falsely detected):* These results showed no significant difference between the two display designs in terms of popup recognition performance.

- *Reaction time to popups*: A 2-tailed paired t-test of these results showed a lack of statistical significance. Plots of these results further/visually confirmed that there was no difference between the two display designs in terms of popup reaction time performance.

- *Number of terrain hazards recognized (& falsely detected):* These results showed no significant difference between the two display designs in terms of terrain hazard recognition performance.

- *Reaction time to terrain hazards:* 2-tailed paired t-tests of these results showed a lack of statistical significance. Plots of these results further/visually confirmed that there was no difference between the two display designs in terms of reaction time performance to hazardous terrain.

The above summary yielded the following conclusions:

Readability of display (1st part of hypothesis)

The popup recognition and reaction time results ultimately disprove our sub-hypothesis that reducing clutter in the conventional multi-colored display will improve the overall readability of the display. The lack of statistical significance in the experimental data has determined that the red contour has no effect on overall readability. On the other hand, subjective data reveals that the red contour improved the subjects' ability to read popups, thus supporting this segment of our hypothesis. This discrepancy in survey and experimental data calls for judgment of the validity of the hypothesis to be based on the stronger data – the objective data. Thus, we ultimately conclude that the red contour and multi-colored design show no difference in the overall readability of the display.

Terrain Awareness (2nd part of hypothesis)

The terrain hazard recognition and reaction time results ultimately confirm our hypothesis that reducing clutter in the multi-colored display has no adverse effects on terrain awareness. The lack of statistical significance in the experimental data determined that the terrain awareness performance for both displays is comparable. However, subjective data disputes this finding, revealing a subjective improvement in terrain hazard recognition using the baseline display. Again, the discrepancy in survey and experimental data calls for judgment of the validity of the hypothesis to be based on the more objective data. Thus, we ultimately conclude that the red contour and multi-colored design show no difference in terrain awareness.

General Conclusion & Further Studies

Results have ultimately showed an equivalent performance between the red contour display and the baseline design. However, it is strongly believed that the instability of the joystick used to fly the simulation (or Microsoft Flight Simulator itself) contributed large errors to these results. As mentioned earlier, subjective comments confirm an inability to maintain altitude and steady vertical speed while flying, thus making the red contour appear sporadic in manner. Had such errors been eliminated, it is believed that the red contour would have experimentally improved overall readability of the terrain display. Hence, further studies in which a more controllable joystick (or more realistic Flight Simulator program) is used are strongly encouraged.

Assessment of Success Criteria

As previously stated, the project was to be a success if data was obtained to determine whether the performance of the reduced cluttered design was

a) <u>better</u> than the baseline's performance,

b) <u>worse</u> than the baseline's performance, OR

c) <u>indeterminate</u> in relation to the baseline's performance due to a lack of statistical significance in the level of difference.

The data from this experiment ultimately meets the third criterion, showing that there is no significant difference between the two display designs. Again, it is strongly believed that the red contour would have performed better than the baseline given the suggestions presented earlier.

8. LIST OF REFERENCES

1. Moroze, Michael L., Snow, Micheal P., "Causes and Remedies of Controlled Flight into Terrain in Military and Civil Aviation," http://www.hec.afrl.af.mil/publications/CFIT990429.pdf, March, 2003.
2. Glover, Howard, "Terrain Displays for Enhanced Ground Proximity Warning Systems," AIAA Paper 97-5557, Sep. 1997.
3. Kuchar, James K., Hansman Jr., R. John, "Part_Task Simulation Study of Candidate Terrain Alerting Displays," 1993.
4. de Muynck, R. J., Khatwa, R., "Flight Simulator Evaluation of the Safety Benefits of Terrain Awareness and Warning Systems," AIAA Paper 99-3965, Aug 1999.
5. Sachs, G., Sperl, R., "Experimental Low Cost 3D-Display for General Aviation Aircraft," AIAA Paper 01-37256, 2001.
6. Sachs, G., Sennes, U., "Design and Flight Test of a Ground Collision Avoidance System," AIAA Paper 99-36810, 1999.
7. Wickens, Christopher. "An Introduction to Human Factors Engineering," Displays, 1998, pp. 223-258.

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10. APPENDICES

APPENDIX A: RAW DATA

The raw data from this project consists of the following:

(Please refer to CD)

Included is a CD of the raw data that was analyzed in this experiment.

APPENDIX B: PRE- & POST-EXPERIMENT SURVEYS

Pre-Simulation Survey

Name:
Age:
Gender:

1. Have you ever piloted an aircraft before? Yes/No

2. If you answered *No* to question 1, skip to question 3.

    a) Do you have a piloting license? Yes/No

    b) How long has it been since you got your license (years)?

    c) What type of aircraft have you flown?

    d) How many piloting hours do you have logged?

    e) When was the last time that you flew? (Please give approximate month/day/year)

    f) How would you describe your skill as a pilot (1 = poor, 7 = excellent):

    1 2 3 4 5 6 7

3. How many hours of experience do you have on Microsoft Flightsim (MSFS)?

4. How often do you use MSFS (everyday, once a week/month/year)?

5. When was the last time that you used MSFS?

6. How would you describe your skill in using MSFS (1 = poor, 7 = excellent)?

    1 2 3 4 5 6 7

7. How many hours of sleep did you get last night?

8. How would you describe your level of alertness today?

    1 2 3 4 5 6 7

8. Do you have any comments relating to the experiment (general conditions, experiences, concerns, etc.)?

*****The subjects were also verbally asked if they had used a TAWS display before**

APPENDIX B: PRE- & POST-EXPERIMENT SURVEYS

<u>Post-Simulation Survey</u>

Name:

On scale of 1to 5 (1 being the *red-contour*, 5 being the *multi-colored design*), rate the display that provided you with BETTER ABILITY TO:

1. View waypoints:

1	2	3	4	5
red-contour		same		multi-colored

2. Recognize and respond to pop-ups:

1	2	3	4	5
red-contour		same		multi-colored

3. Follow the planned flight course:

1	2	3	4	5
red-contour		same		multi-colored

4. Discern hazardous terrain:

1	2	3	4	5
red-contour		same		multi-colored

5. Read information other than terrain data:

1	2	3	4	5
red-contour		same		multi-colored

Other

6. Which display do you prefer? Why?

7. Any comments:

Thank you for your participation!!!

APPENDIX C: SOFTWARE MODULE DESCRIPTION

Overview
This document provides a top-level description of the software implemented for this project. The entire software structure takes as input user input data, MSFS aircraft parameters (longitude, latitude, altitude, heading, speed, vertical speed), terrain data file, and popup data file; the outputs of this software include on screen displays of TAWS and output data to file. Key data structures within the code are handled globally to save both memory space and processing time. Therefore, in the sections below, inputs and output to a module refers to the variables used and changed by the module, not actual inputs and outputs of functions. Functions under the FSUIPC are written in one file while functions under the Popup Database and Display modules are placed in another. Each of these files have its own header file. All other functions are located in the same file as the C++ main() function.

Terrain Database Module
This module only contains one function, void readTerrainData (void). This function reads in terrain information from a data file and saves the information in variable float terrainDataList[][]. The only other variable used by this function is const double altitudeScaleFactor, a multiplicative factor for the altitude of the input terrain. With this variable, the effective altitude of the terrain can be adjusted at will.

Popup Database Module
This module contains several functions that read popup data from a database text file, stores the information into a variable, and display the popups onto screen. This module also contains code that moves the popups across the screen.

FSUIPC Module
This module extracts from MSFS aircraft parameters (longitude, latitude, altitude, heading, speed, and vertical speed), and sends the information to the TAWS Setup Module

TAWS Setup Module
This module takes in terrain and aircraft information and finds the piece of terrain that should be displayed on the TAWS, along with the expected time to impact of the aircraft with terrain given the current heading, speed, and vertical speed. The module contains the following functions:

- void acParamConvFunc (void) converts aircraft longitude and latitude position into x and y positions in nmiles. The (x, y) position is referenced to (0, 0) at the beginning of the simulation.
- void findTawsPosition (void) uses the current converted aircraft information to find the location of the aircraft within the terrain scenario world. Then uses the location of the aircraft, aircraft heading, and the relative sizes of the TAWS and scenario world to find the location of the bottom left corner of the TAWS in the scenario world
- void findTawsTerrain (void) uses the position of the TAWS and current aircraft heading to find the terrain that should be displayed on the TAWS screen

- void findImpactTime(void) uses to TAWS terrain information and current aircraft speed to find the expected time to impact of the aircraft with terrain

TAWS Setup Module Inputs

Variable Name	Data Type	Description
worldSize	const double	The size of the terrain scenario world in nmiles
tawsToWorldRatio	const double	The size of the TAWS relative to the scenario world
acParamInit[6]	double	The initial set of 6 aircraft parameters at the beginning of the simulation
acParamList[6]	double	A set of 6 aircraft parameters at any time point during the simulation
terrainDataList[][]	float	Terrain data information

TAWS Setup Module Outputs

Variable Name	Data Type	Description
acParamConv[6]	double	A set of converted aircraft parameters
tawsTerrainList[][]	float	Terrain data that should be displayed on the TAWS
tawsPosition[5][2]	double	The position of the aircraft and TAWS in the terrain scenario world
impactTime	double	The expected time to impact of aircraft with terrain

TAWS Display Module

This module displays the terrain information along with the course markers, time to impact, aircraft symbol, and TAWS grid. The module contains the following functions:

- void displayTerrain(void) displays the TAWS terrain information. This is the one function that differs from the multi-colored to the red-contour display
- void displayMarkers(void) displays the 2 course markers into the TAWS screen
- void displayAC(void) display the symbol of the aircraft at the bottom of the TAWS
- void displayGrid(void) displays a grid on the TAWS screen. The grid consists of the one line along the current heading of the aircraft along with 2 other lines 30 degrees to either side of the current heading. The function also displays 4 circular arc at ¼, ½, ¾, and end of the TAWS display
- void displayImpactTime(void) displays the time to impact at the bottom right corner of the TAWS

This module does not have any output variables, only display outputs to screen.

TAWS Display Inputs

Variable Name	Data Type	Description
headingChangeMarker[2]	const double	The location of the second marker on the display
altLevelOffMarker[2]	const double	Location of the first marker on the display
tawsTerrainList[][]	float	Terrain for the TAWS display
impactTime	double	Time to impact of the aircraft

Data Collection Module
This module is responsible for collecting all relevant data variables from the rest of the code and outputting their values to file. The module contains the following functions:

- void headerInputPrompt (void) is responsible for prompting for relevant user input data such as subject name, scenario number, date, time, etc.
- void headerOutput(void) is responsible for outputting the subject and scenario information along with initial one time variables such as initial aircraft position, marker locations, etc.
- void mainDataOutput (void), void userDataOutput(), and void popupDataOutput() are three functions responsible for outputting data during each iteration of the code.
- void endDataOutput (void) ends the data output file.

The inputs to this module and this module's outputs to file are one and the same.

Data Collection Module Inputs

Variable Name	Data Type	Description
simulationTimeStart	double	Machine time at the start of the simulation
simulationTimeCurrent	double	Machine time at any given point during the simulation
tawsOrder	int	Stores which TAWS the subject used first
subjectNumber	int	Subject number assigned to each subject (1-12)
scenarioOrder	int	For this subject, what is the testing order number for this scenario (1-8)
lastName[10]	char	Last name of subject
firstName[10]	char	first name of subject
date[11]	char	mm/dd/yy of test
startTime[8]	char	h:m am/pm
worldSize	const double	The size of the terrain scenario world in nmiles
tawsToWorldRatio	const double	The size of the TAWS relative to the scenario world
headingChangeMarker[2]	const double	The location of the second marker on the display

altLevelOffMarker[2]	const double	Location of the first marker on the display
acParamConv[6]	double	Set of 6 aircraft parameters with longitudes and latitudes converted in x and y positions. (x, y, altitude, heading, speed, vertical speed)
impactTime	double	Time to impact with terrain
popuppress	struct	User recognition of popups
popup_data	struct	Information on a pop-up. (letter, altitude, initial x pos, initial y pos)

Data Compilation Module
This is the only software module that does not run real time during the experiment. This module is written in *Mathematica* and is used to reduce the massive amount raw data produced by the data collector. This module outputs the data analyzed in this report.