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Usability and Effectiveness of Advanced General Aviation Cockpit Displays for Instrument Flight Procedures

Kevin W. Williams
Jerry D. Ball
Civil Aerospace Medical Institute
Federal Aviation Administration
Oklahoma City, OK 73125

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16. Abstract

A study was conducted to assess the impact of advanced navigation displays on instrument flight procedures for general aviation, single-pilot operations. The study was designed to identify human factors that should be considered during the deployment of this technology to the entire general aviation community and in the development of future displays. The study focuses on single-pilot operations during normal to high workload conditions, including a failure of the vacuum-driven cockpit displays. Sixteen IFR-rated pilots were asked to plan and fly two separate flights in instrument conditions, once using conventional instrumentation, and once using a moving-map/GPS display combination. Results show advantages for the advanced displays in flight performance under high-workload conditions. However, training requirements for these displays are likely to be increased relative to conventional navigational instruments.

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INTRODUCTION

More than three years ago, the Federal Aviation Administration instituted the Alaska Capstone Program in an effort to improve flight safety in Alaska (FAA, 2003). The Capstone Program provided for the installation of new cockpit avionics for over 150 general aviation (GA) aircraft in the southwest region of Alaska, centered around the town of Bethel. The avionics system, developed by UPS Aviation Technologies, consisted of a multi-function display (MFD) unit, the Apollo MX-20, and an accompanying Global Positioning System (GPS) display, the Apollo GX-60. In addition, each aircraft was equipped with a Universal Access Transceiver (UAT), which provided datalink communication between the aircraft and a ground station

Figure 1: Capstone Avionics displays. The MX-20 display is shown on top and the GX-60 GPS unit is shown below it.

or from one aircraft to another aircraft. Figure 1 shows the Capstone avionics displays.

The two Capstone displays provided pilots with a moving map that shows ownship (i.e., own aircraft) position. Routes entered into the GPS display are presented as a magenta line on the moving map. The map can display an instrument flight chart, with airways, intersections, airports, and other navigational points or a visual flight rules (VFR) sectional chart that includes terrain features. Many types of information can be overlaid on the map at the pilot's discretion. For example, the display can also show the relative height of terrain in the form of red, green, yellow, or black colored blocks. Using a custom map page, pilots can overlay terrain with airport and other information. The display also provides traffic and weather information to the pilot. Traffic information is dependent on a ground/air/space infrastructure known as Automatic Dependent Surveillance - Broadcast, or ADS-B. In addition, weather information is uplinked to the pilot through a system known as Flight Information Services - Broadcast, or FIS-B, from weather reporting stations.

Interviews with pilots participating in the Capstone Program have provided significant insight into the impact of this technology on flight operations (Williams, Yost, Holland, & Tyler, 2002). The pilots interviewed have been mostly positive. Still, some system features have been identified as needing improvement. While information gained from the interviews will assist in the transition of this type of technology to aircraft in the rest of the U.S., individuals participating in the Capstone Program were all 14 CFR Part 135 pilots (i.e., professional pilots), flying almost every day of the year. Consequently, the majority of these pilots fly over 100 hours each month, and nearly all (95%) are instrument rated.

This leads to the obvious question of the impact of this kind of technology on the 14 CFR Part 91 (i.e., non-professional) pilot population. Part 91 pilots typically fly much less often, and a significant portion of this population does not have an instrument rating (FAA, 2000). In addition, the Part 91 population is more diverse, having a wider range of total flight experience and ages. What is needed is an examination of the effect of these displays on the Part 91 pilot population. The present study was designed to identify human factors that should be considered during the deployment of this technology to the entire general aviation community and in the development of future displays.

When examining Part 91 flight activities, two pilot groups should be considered before transitioning this equipment to the GA pilot population. One group consists of low-time pilots who would only use the displays in VFR conditions because they do not have an instrument rating. While their flight tasks are simpler, they typically have fewer resources to assist them and, as such, represent an interesting group for study. A future study will examine this pilot group.

The other group consists of pilots who will use the multi-function navigational displays in instrument flight. Instrument flight is one of the most complex aspects of single-pilot operations. This complexity is exacerbated when using a GPS display because of the type and amount of user interaction required to operate the equipment. Prior research has indicated that GPS displays are among the most complex equipment that most Part 91 pilots interact with in the cockpit (Williams, 1999a), and that GPS user-interface design deficiencies tend to exacerbate the difficulty of using these displays (Nendick, 1995; Nendick & St.George, 1995; Heron & Nendick, 1999; Wickens, 2000; Williams, 1999a, 1999b). The current study was designed to examine the usability of these advanced displays for instrument flight activities and to compare the effect that the displays have during instrument flight on pilot performance and workload relative to standard navigation instruments. The study focuses on single-pilot operations during normal to high workload conditions, including a failure of the vacuum-driven cockpit displays.

METHODS

Participants

Sixteen instrument-rated pilots were recruited from the Oklahoma City metropolitan area and were compensated monetarily for their participation. All of the pilots were male, with the average age of 29.75 years, a median age of 25 years, and a range in ages from 21 to 69 years. The participants were asked to estimate the number of flight hours for several categories of flight. They were also asked whether they had used a cockpit GPS or multi-function display and if they had used a flight simulation program similar to the one employed in the study. This information is summarized in the Results section.

Design

In the current study, pilots were asked to plan and fly two separate flights in instrument conditions. During one flight, pilots were permitted to use only a standard navigational instrument (i.e., VOR), instrument charts, and sectional charts. During the other flight, pilots were asked to conduct the flight using the GX-50[1] GPS and MX-20 multi-function displays. Both flights included a

[1] There is no difference in the user-interface of the Apollo GX-60 and GX-50 displays. The GX-60 display has additional functionality that was not required for the experiment.

number of instrument procedures commonly required during instrument flight, as well as a vacuum failure, designed to subject the pilot to a high workload while interacting with the displays.

Measurement Instruments

Usability, workload, and pilot performance were gauged using a number of subjective and objective measures. Usability measures primarily focused on the GX-50 and MX-20 displays. No evaluations of usability of the VOR navigational display were performed. A usability questionnaire was administered to each pilot to gauge various aspects of the GX-50 and MX-20 displays. Six rating criteria (effectiveness, ease of use, workload, cues and prompts, system feedback, and head-down time) were scored using a 5-point Likert scale for each of the display's features and functions. A copy of the questionnaire is reproduced in the appendix. In addition, button presses were videotaped to measure interaction errors. An experimenter was available to assist the pilot on use of the displays during the flights. Experimenter assistance on tasks was recorded.

The NASA TLX subjective workload questionnaire (Hart & Staveland, 1988) was administered to each pilot to get a subjective measure of workload for several of the in-flight tasks. NASA TLX is a six-item questionnaire measuring mental effort, physical effort, temporal pressure, perceived performance, total mental and physical effort, and frustration. Immediately after a selected in-flight task, the pilot was asked to give a score (1 meaning low and 10 meaning high) for each of the six items.

Equipment

All of the flights were conducted in the Civil Aerospace Medical Institute's Basic General Aviation Research Simulator (BGARS), comprised of seven networked PCs using Microsoft's Flight Simulator 2002, five out-the-window views, and moderate-fidelity controls (Precision Flight Systems – Dual Professional Flight Console). Flight performance data were recorded four times per second and consisted of latitude, longitude, altitude, ground speed, heading, bank, cross-track error, elapsed time, and flight segment. The simulator was configured as a Cessna 182RG for this study. Figure 2 shows a picture of the simulator. Figure 3 shows how the GPS and MFD were situated in relation to the rest of the aircraft instruments.

Figure 2: Basic General Aviation Research Simulator (BGARS).

Figure 3: Close-up view of aircraft instruments and GPS/MFD displays (to the right).

Procedure

Pilots filled out the required consent forms and then were briefed about the experimental protocol. Each pilot received approximately two to three hours of training on the GX-50 and the MX-20. The training began on the GX-50 by demonstrating the differences between the two types of keys (smart and hard keys) and the functions associated with each key. Specifically, the pilots were taught how to perform a series of tasks that they later would be required to perform during the flight. During the training, the pilots were required to demonstrate minimal proficiency with the GX-50, measured as one unassisted completion of the task, to perform the following tasks:

- Go direct to a waypoint;
- Extract information about various waypoints;
- Build, edit, and modify an active or saved flight plan;
- Navigate using the course deviation indicator (CDI) on the GPS display;
- Set up and enter holding procedures;
- Load and change approaches; and
- Perform missed approach procedures.

Next, the pilots were shown how to use the MX-20. The four different map modes (VFR, IFR, Terrain, and Custom) were shown to the pilots. Within each mode, the menu structure was explained, and detailed instructions were given on how to select the map orientation (North-up, track-up, and desired track-up) and appearance (declutter options and overlays). Last, the flight plan page was explained to each of the pilots. Breaks were provided to the participants as required.

Following the training, a 20-minute warm-up flight was given to the pilots to allow time for familiarization with the simulator and to be sure that the pilots could perform the necessary instrument flight tasks. At the conclusion of the warm-up flight, a 15-minute break was given to each pilot.

The experimental procedure required that the pilots fly two similar IFR flight plans in instrument meteorological conditions. When following one flight plan, pilots were required to navigate using only the GX-50 and MX-20, while the other flight plan required the pilots to navigate using only a VOR head. GPS approaches were flown with the GX-50 and MX-20, and VOR approaches were flown in the VOR condition. Pilots had access to all appropriate paper charts (U.S. Terminal Procedures charts, Sectional Aeronautical chart, and IFR En Route Low Altitude charts) during both flights. Pilots were free, both before and during the flight, to set up and adjust their MX-20 map display at their discretion.

The first flight scenario consisted of flying from Hanscom Field, in Bedford, Massachusetts (BED), to the Gardner (GDM) VORTAC. Shortly after takeoff, pilots were redirected to fly the 100-degree radial inbound at GDM to avoid a restricted flight zone. Before reaching GDM pilots were given instructions to hold at the HURLY intersection on the 298-degree radial and then fly an approach into Keene Dillant-Hopkins (EEN) airport. At the missed approach point, pilots were instructed by air traffic control (ATC) (the experimenter) to fly the published missed approach course back to the Keene VORTAC (EEN); before reaching Keene, they were directed to fly an approach into an alternate airport (Jaffery, AFN). Figure 4 shows the area of the flight. The thick shaded lines show the basic flight segments used to measure flight path error during the flight.

The second flight scenario was the same as the first flight except the pilots were required to hold at the LAPEL intersection on the 246-degree radial instead of at the HURLY intersection. ATC then cleared the pilots for an approach into Orange County (ORE). At ORE, the pilots flew the published missed approach. Pilots were then instructed to fly an approach into the alternate airport, KEEN. Figure 5 depicts the flight area with shaded lines indicating flight segments used to measure flight path error.

During both flights, a vacuum system failure occurred when the pilots were 10 miles from the alternate airport. The pilots were required to fly the approach into the alternate airport using partial-panel instrumentation and/or the GX-50 and MX-20. Data collection was terminated shortly before the aircraft reached the alternate airport, and pilots were not required to land.

The weather was set to ¾ of a mile visibility for both flights. Winds were 10 knots from 260 degrees, which was a slight crossing headwind for most of the flight. Each flight scenario lasted approximately 75 minutes, and a 15-minute break was given to each pilot between the flight scenarios. The order of the GPS and VOR navigation conditions and flight plans was counter-balanced across participants. At the conclusion of the second flight, the usability questionnaire was administered to the pilots, and then they were debriefed.

Hypotheses

- It was expected that measures of workload would generally favor the standard flight instruments. This expectation was based on the literature (cited above) documenting the complexity of the GPS and specific user-interface design problems. However, it was possible that workload would be mitigated somewhat due to the presence of the MX-20 moving-map display.
- In contrast to workload, it was expected that flight performance measures would generally favor the GX-50/MX-20. Prior research has shown that the use of horizontal situation displays such as the MX-20 improves navigation performance (Haskell & Wickens, 1993; Wickens & Prevett, 1995).

Figure 4: First flight scenario.

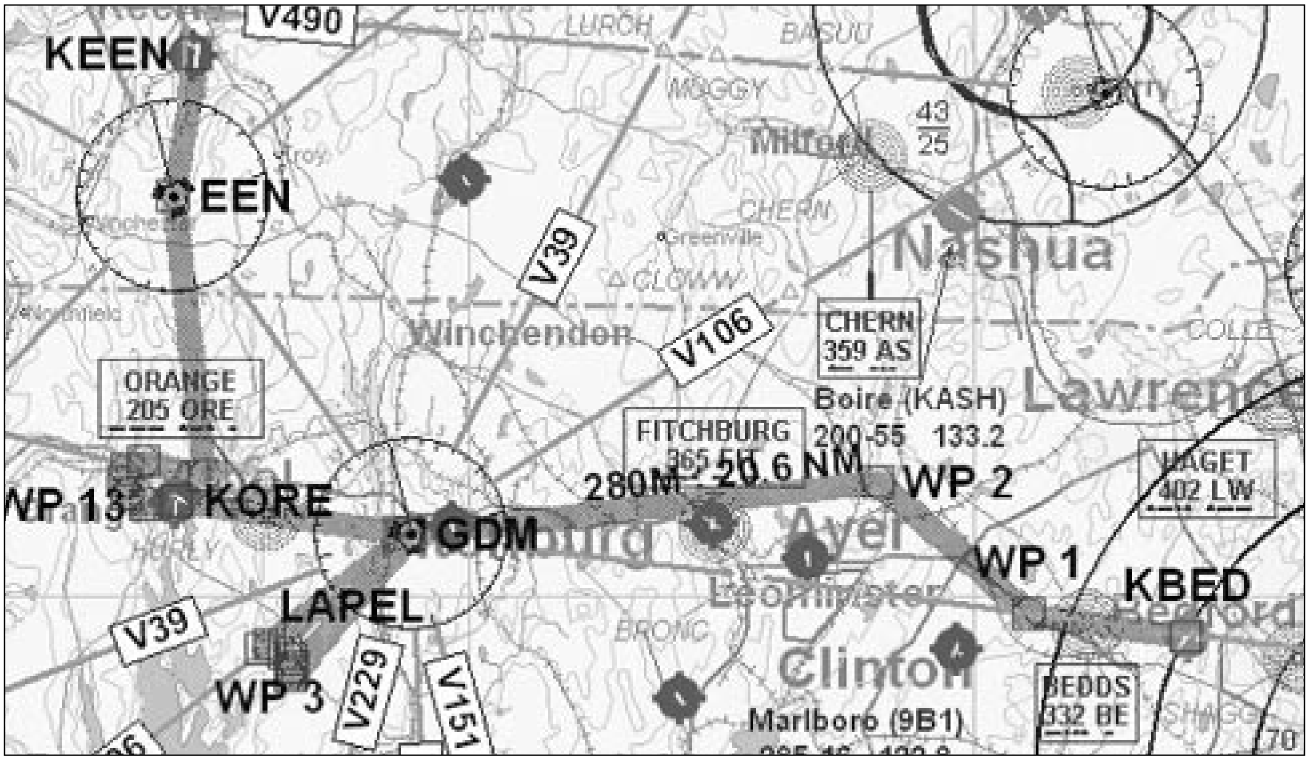

Figure 5: Second flight scenario.

- Finally, it was expected that the use of the GX-50/MX-20 displays would have beneficial effects on both navigational performance and workload during the vacuum pump failure, because the new displays would compensate for the resulting loss of information (e.g., loss of attitude indicator and heading indicator).

RESULTS

Pilot Demographics

Flight hour estimates were collected for a number of flight categories. The mean, median, and range of each category are presented in Table 1.

In addition to flight hours, participants were asked to report on their use of personal computer-based flight simulator programs similar to the Microsoft Flight Simulator 2002 program used in the current study. Twelve of the sixteen pilots (75%) had used Microsoft Flight Simulator or a similar program. Mean total use of the programs was estimated as 21.43 hours. Median use was 10 hours, ranging from 0 to 150 hours.

Participants were also asked whether they had used any type of GPS navigation display while flying. Eleven of the pilots (69%) stated they had used a GPS display. Mean total use time for those who had used a display was 25.5 hours. Median use was 16 hours. Finally, participants were asked whether they had used a moving map system similar to the MX-20 display used in the current study. Three of the pilots (19%) said they had used such a display prior to the study.

Display Usability

All participants were asked to rate how easy it was to learn to operate the display system. Ratings were obtained on a 5-point scale from 1 (very difficult to learn) to 5 (very easy to learn). The mean rating was 3.67, with no rating below a 3 (i.e., average difficulty to learn). Finally, pilots were asked whether they would like to use the navigation system in a real aircraft. Twelve of the pilots (75%) said they would like to use the system in real flight.

After completing both of the flights, participants filled out the usability questionnaire. MX-20 and GX-50 features were rated according to each of 6 criteria along a 5-point scale. A higher number indicated better usability for each of the criteria. The reader is directed to the Appendix for the definitions of the rating scale values. Table 2 presents the mean ratings for the MX-20 features on each of the 6 usability criteria.

In the Table, the shading indicates the two highest ratings for a particular criterion. Ties occurred for some of the criteria. Only two mean scores fell below 3.0. These scores are highlighted using bold text and borders. The Table indicates that pilots believed that the map range (zoom) feature and the map information were the most usable aspects of the MX-20. During normal operation, two buttons were continuously dedicated for zooming,

Table 1: Pilot Flight Time Demographics.

Demographic Category	Mean Hrs.	Median Hrs.	Range Hrs.
Total Time	1954.38	405.00	145 - 20,000
Time: Last 12 Months	248.75	170.00	20 - 950
Time: Last 90 Days	85.73	80.00	2 - 450
Total Time: VFR	1729.13	365.00	115 – 18,000
VFR Time: Last 12 Months	222.44	152.00	20 - 800
VFR Time: Last 90 Days	63.50	38.50	0 - 375
Total Time: Actual Instrument Flight	198.89	6.00	1 – 2,000
Actual Instrument Time: Last 12 Months	13.06	4.00	0 - 85
Actual Instrument Time: Last 90 Days	4.34	1.25	0 - 25
Total Time: Simulated Instruments	119.06	52.50	20 – 1,000
Simulated Instrument Time: Last 12 Months	34.00	23.50	0 - 100
Simulated Instrument Time: Last 90 Days	13.69	4.00	0 - 50

making it easy for the pilots to alter the zoom level. The lowest scores for all of the MX-20 features were those related to head-down time.

In addition to the functions listed in Table 2, pilots were asked specific questions about the usability of a number of other features of the MX-20. Ratings ranged from 1 to 5 on a disagree-agree scale. These questions, and their mean response values, are listed in Table 3.

Looking at Table 3, we find that most of the items were rated highly by the pilots. Items 4, 5, and 16, which all dealt with situation awareness, and specifically with position awareness, were the most highly rated items. The lowest-rated item was the statement, "Prompts for pilot inputs, alerts, and advisories effectively attracted my attention." It should be noted that pilot alerts and advisories were visual only, with no aural cue accompanying the alert. Of the alerts and advisories available on the MX-20, the only ones that the pilots regularly experienced during the experiment were a terrain warning flag and a barometric pressure confirmation.

Pilots also rated GX-50 features according to the same six usability criteria. Table 4 presents the mean feature ratings for the GX-50.

The GX-50 feature rated most usable was the Nearest Airport function. Pilots also were particularly satisfied with the display of cross-track error data. As with the MX-20, the lowest ratings occurred for head-down time. However, workload ratings were a close second.

The usability of additional features was addressed with specific questions, including four items (28-31) on the effectiveness of the MFD/GPS displays during the vacuum failure (see Table 5). As before, these questions were rated on a disagree-agree scale of 1 to 5.

The GPS usability item receiving the lowest rating concerned the ability of the unit to attract pilot attention for warnings and alerts. The alerts received by pilots during the study were messages regarding the completion of flight segments and warnings regarding approach to restricted flight areas. As with the MX-20, no aural alerts were issued by the GPS.

In addition to the specific usability questions, participants were asked if they had made any errors while interacting with the MX-20 and GX-50 displays. Five (31%) of the participants stated they had made errors with the MX-20. Seven (44%) participants admitted making errors with the GX-50. In general, when asked to comment on the errors they committed, participants stated they could not remember how to perform particular functions and so performed them incorrectly. Many of these pilots added that they would not have made errors if they had been given more time to learn how to use the displays.

To measure the pilot's subjective estimates of how easy it was to handle the vacuum failure both with and without the MFD/GPS equipment, paired t-tests were conducted to compare item 28 with 29 and item 30 with 31. Items 28 and 29 asked the pilots to judge how easy it was to control the aircraft after the vacuum failure while referencing only conventional navigation instruments or using the MFD/GPS. Items 30 and 31 asked the pilots to judge ease of navigating after the vacuum failure using either conventional navigation instruments or the MFD/GPS. Both paired t-tests indicated significant differences between the items, showing that pilots believed it was easier to control the aircraft after the vacuum failure using the MFD/GPS, $t(13) = 2.88$, p

Table 2: MX-20 mean feature ratings on six usability criteria.

	Feature Rating Criteria						
Part 1. Multifunction Display	**Effect-iveness**	**Ease of Use**	**Work-load**	**Cues & Prompts**	**Feed-back**	**Head Down Time**	**Row Mean**
Accessing database information (runway length, frequencies, etc)	4.14	3.50	3.36	3.43	3.86	**2.79**	**3.51**
Selecting terrain mode	3.77	3.46	3.38	3.62	3.69	**2.92**	**3.47**
Map type selection (VFR, IFR, Custom)	4.14	4.00	4.00	3.79	4.14	3.64	**3.95**
Adjusting altimeter setting	3.82	4.36	4.00	3.82	4.00	3.00	**3.83**
Map orientation selection (North up, Track up)	4.23	3.77	3.54	3.85	3.85	3.31	**3.76**
Selection of map data for display – decluttering	4.00	3.86	3.79	4.00	3.86	3.14	**3.78**
Using navigation data	4.29	3.93	3.71	3.79	3.64	3.50	**3.81**
Using the map range (zoom) feature	4.50	4.36	4.21	4.14	4.00	3.86	**4.18**
Using an approach procedure	4.00	3.86	3.36	3.50	3.79	3.14	**3.61**
Selecting the Pan mode	3.82	3.82	3.91	3.82	3.55	3.18	**3.68**
Panning the map	4.09	4.09	3.91	3.73	3.82	3.27	**3.82**
Using map information	4.36	4.29	4.14	3.86	4.00	3.43	**4.01**
Using terrain information	4.07	3.71	3.64	3.57	3.50	3.29	**3.63**
Column Mean	**3.80**	**3.64**	**3.50**	**3.49**	**3.55**	**3.03**	

$<.05$, and that it was easier to navigate after the vacuum failure using the MFD/GPS, $t(13) = 4.01$, $p < .05$, relative to using conventional navigation instruments. It should be noted that for both tests, two of the participants did not respond to the items, and so their data were excluded from the analysis.

Display Interaction Analysis

Participants were videotaped during their interaction with the MX-20/GX-50 displays. These videotapes were reviewed so that counts could be made of the number of actions taken by participants to complete each of their tasks, whether or not they received help from the experimenter. In addition, the experimenter noted whether assistance was required, in the form of explicit instructions from the experimenter, to complete a task. Excess actions were computed by counting the number of actions taken to complete a particular task and subtracting the minimum number of actions required. Figure 6 shows the mean number of excess actions taken by participants by task.

Looking at Figure 6, we see that participants used more excess button presses while interacting with the GPS display than when they were interacting with the MFD. The GPS task showing the most excess activations was inserting an assigned intersection into the flight plan prior to conducting a holding procedure. This task required the input of letters and numbers into the display through the use of both buttons and knobs. Likewise, the task with the second-most activations, entering the alternate airport into the flight plan, also required the participants to input letters and numbers into the display.

In addition to counting the number of excess button presses, experimenters recorded whether or not pilots required assistance to complete specific tasks. Usually, such assistance consisted of explicit instructions regarding which buttons to press and which knobs to turn. Figure 7 shows the percentage of pilots requiring assistance to complete each of the tasks.

As with the excess control activations, participants had less trouble with the MFD than they did with the GPS. Again, we found that two of the most difficult tasks for the pilots involved entering letters and numbers into the GPS display. However, for every GPS task, at least 50% of the pilots required assistance to complete the task.

Subjective Workload Estimates

The six individual workload estimates for a task were averaged into a single composite workload estimate for that task. Figure 8 presents a bar graph of the composite scores for each of seven tasks, separated by display type (GPS/MFD vs. VOR).

A two-way analysis of variance (Flight Task x Display Type) was conducted on the composite workload scores. The only factor that reached significance was Flight Task, $F(6, 78) = 26.94$, $p < .01$. No effect for Display Type was found, and there was no interaction effect. A post hoc comparison

Table 3: Mean scores for additional MX-20 (MFD) usability items.

1. Overall, the GPS/MFD increased my awareness of nearby terrain relative to conventional instruments.	4.40
2. The terrain proximity feature attracted my attention to terrain in a timely fashion.	4.13
3. The GPS/MFD increased my awareness of my ground speed, course, and altitude relative to conventional instruments.	4.13
4. The GPS/MFD increased my awareness of my position relative to airports, fixes, and airways relative to conventional instruments.	4.87
5. The GPS/MFD increased my awareness of my position during instrument approaches relative to conventional instruments.	4.93
6. The MFD information I needed was easy to see and not obscured by other information.	4.40
7. Text displayed on the MFD was easy to read.	4.13
8. The meaning of symbols and text on the MFD was easy to understand.	4.40
9. Prompts for pilot inputs, alerts, and advisories effectively attracted my attention.	3.27
10. Prompts for pilot inputs, alerts, and advisories were easy to understand.	3.93
11. The MFD menus were easy to use.	4.07
12. The MFD menu options were easy to understand.	4.07
13. The MFD button labels were easy to understand.	4.20
14. Information about fixes shown on the MFD maps was easy to obtain.	3.80
15. The use of colors on the MFD maps was meaningful.	4.53
16. I remained geographically oriented while I changed heading.	4.73
17. I remained aware of ownship position when I panned the MFD map.	4.21
18. The size of the MFD display area was adequate for the information presented.	4.53

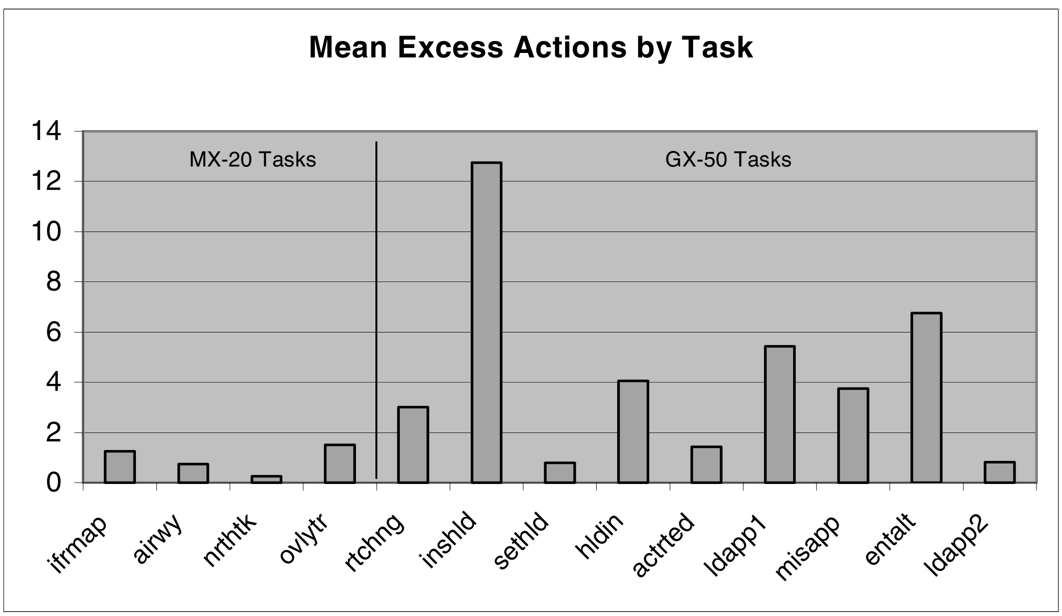

Figure 6: Mean number of excess actions, by task, taken by pilots using the MX-20 and GX-50 displays. **Key** – **ifrmap** = change to IFR map display; **airwy** = remove high altitude airways from IFR map; **nrthtk** = change map display mode from north-up to track-up; **ovlytr** = select custom map and overlay relative terrain; **rtchng** = set GPS to intercept assigned radial; **inshld** = insert assigned intersection into flight plan for holding procedure; **sethld** = select assigned outbound radial for holding procedure; **hldin** = set inbound radial for hold procedure; **actrted** = reactivate auto-sequencing; **ldapp1** = load the first approach; **misapp** = activate the missed approach procedure; **entalt** = enter the alternate airport into the flight plan; **ldapp2** = load the approach to the alternate airport.

Table 4: GX-50 mean feature ratings on six usability criteria.

	Feature Rating Criteria						
Part 2. GPS Navigator	**Effect-iveness**	**Ease of Use**	**Work-load**	**Cues & Prompts**	**Feed-back**	**Head Down Time**	**Row Mean**
Accessing database information (runway lengths, frequencies, etc)	3.69	3.38	3.38	3.85	4.00	**2.77**	**3.51**
Entering flight plans	4.00	3.23	3.15	3.77	3.92	3.08	**3.53**
Editing flight plans	3.69	3.15	**2.85**	3.54	3.92	**2.92**	**3.35**
Selecting "Direct To" function	3.92	3.69	3.23	4.15	4.00	3.31	**3.72**
Using GPS navigator to fly a radial to/from a waypoint	3.69	3.54	3.38	3.62	3.62	3.08	**3.49**
Using GPS navigator to fly a holding pattern	3.31	3.46	3.00	3.69	3.54	**2.92**	**3.32**
Loading and flying GPS approaches	3.77	3.77	3.38	3.92	3.69	3.08	**3.60**
Using the CDI data	3.75	3.58	3.33	3.58	3.83	3.33	**3.57**
Using cross-track error (XTE) data	3.92	4.00	3.83	3.58	3.50	3.58	**3.74**
Using DTK data	3.42	3.42	3.25	3.83	3.50	3.33	**3.46**
Using Message information	3.23	3.23	3.38	3.54	3.69	3.58	**3.44**
Accessing flight plan leg information	3.85	3.38	3.15	3.92	4.00	3.31	**3.60**
Using the Nearest (airport) function	4.25	3.92	3.67	4.08	4.25	3.83	**4.00**
Column Mean	**3.46**	**3.27**	**3.07**	**3.51**	**3.53**	**3.01**	

Table 5: Mean scores for additional GX-50 (GPS) usability items and vacuum failure questions.

1. It was easy to enter data into the GPS receiver.	3.86
2. The knobs and buttons on the GPS receiver were placed in logical and convenient locations.	4.21
3. The GPS receiver controls for different functions operate in a consistent manner.	4.00
4. Text on the GPS display was easy to read.	4.57
5. The size of the GPS display area was adequate for the information displayed.	4.07
6. It was easy to select GPS information (airports, airport information, VORs, waypoints, etc.).	4.00
7. It was easy to select a GPS approach.	4.29
8. GPS warnings and alerts were issued at the right time.	4.00
9. GPS warnings and alerts effectively attracted my attention.	3.14
10. It was easy to control the airplane after the vacuum failure using the MFD/GPS.	4.14
11. It was easy to control the airplane after the vacuum failure using only conventional instruments.	3.14
12. It was easy to navigate after the vacuum failure using the MFD/GPS.	4.64
13. It was easy to navigate after the vacuum failure using only conventional instruments.	3.14

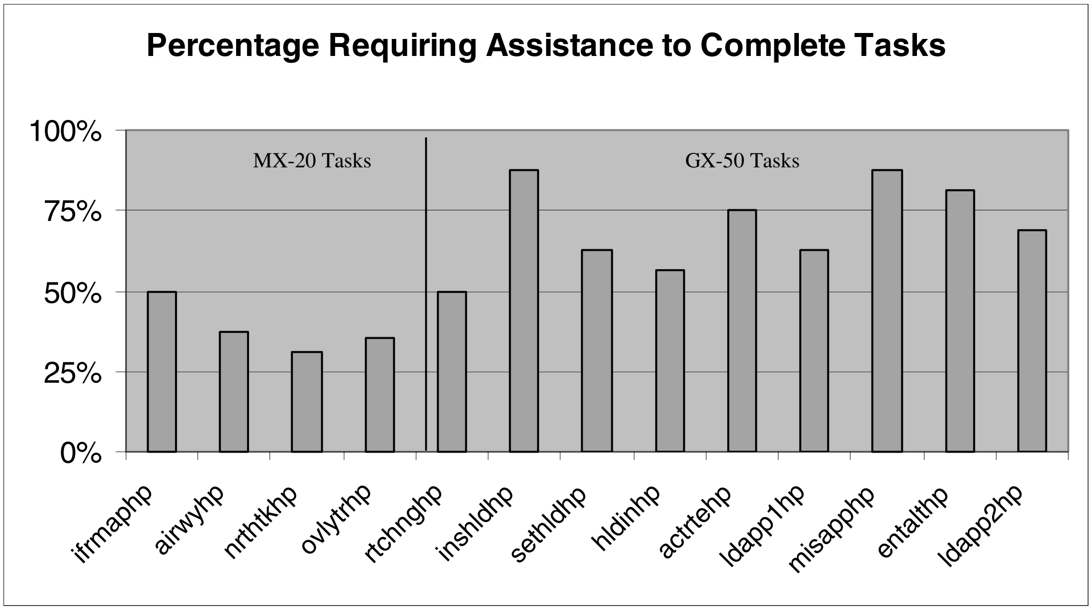

Figure 7: Percentage of pilots, by task, requiring assistance to complete specific user-interface tasks. **Key** – **ifrmap** = change to IFR map display; **airwy** = remove high altitude airways from IFR map; **nrthtk** = change map display mode from north-up to track-up; **ovlytr** = select custom map and overlay relative terrain; **rtchng** = set GPS to intercept assigned radial; **inshld** = insert assigned intersection into flight plan for holding procedure; **sethld** = select assigned outbound radial for holding procedure; **hldin** = set inbound radial for hold procedure; **actrted** = reactivate auto-sequencing; **ldapp1** = load the first approach; **misapp** = activate the missed approach procedure; **entalt** = enter the alternate airport into the flight plan; **ldapp2** = load the approach to the alternate airport.

of levels within Flight Task showed that the last four tasks were judged to have produced significantly higher workload than the first three tasks, $t(15) = 10.048$, $p < .01$.

Pilot Performance Analysis

A number of flight-performance variables were collected during the flights. The most important variables were cross-track error and altitude since these are most directly related to distance from a desired course. Additional performance data included bank, ground speed, and heading. Each flight was divided into 9 flight segments for the purpose of analyzing specific flight-performance variables. Not all of the segments were useful for analysis and not all of the performance variables were valid for every segment. For example, Segment 1 was from takeoff until the pilot turned to intercept the 100 degree radial. No differences in course deviation were expected as a result of display differences during this segment. Also, altitude changes continuously during an approach segment. Because glide-slope information was unavailable, the analysis of altitude during this segment would not be useful.

Figure 9 shows the root-mean-square cross-track error, by display type, for three flight segments. The inbound radial segment refers to tracking the radial inbound toward a VOR. After reaching the VOR, pilots turned to a new heading and followed an outbound radial until they reached a designated intersection. The final approach segment occurred after the vacuum failure while the pilot was flying with partial-panel instrumentation. Paired t-tests were used to compare cross-track error differences between display types for each segment. The inbound radial segment showed a significant difference according to display type, $t(15) = 2.20$, $p < .05$, as did the final approach segment, $t(15) = 3.14$, $p < .05$. In both cases, use of the GPS/MFD led to significantly less error relative to use of the VOR.

Much of the difference in cross-track error can be attributed to the fact that the VOR signal spreads out as it moves away from the emitter, unlike the GPS cross-track indication, which remains constant at all positions. This could explain why VOR flight performance on the outbound radial showed much less cross-track error than on the inbound radial: because the outbound radial was

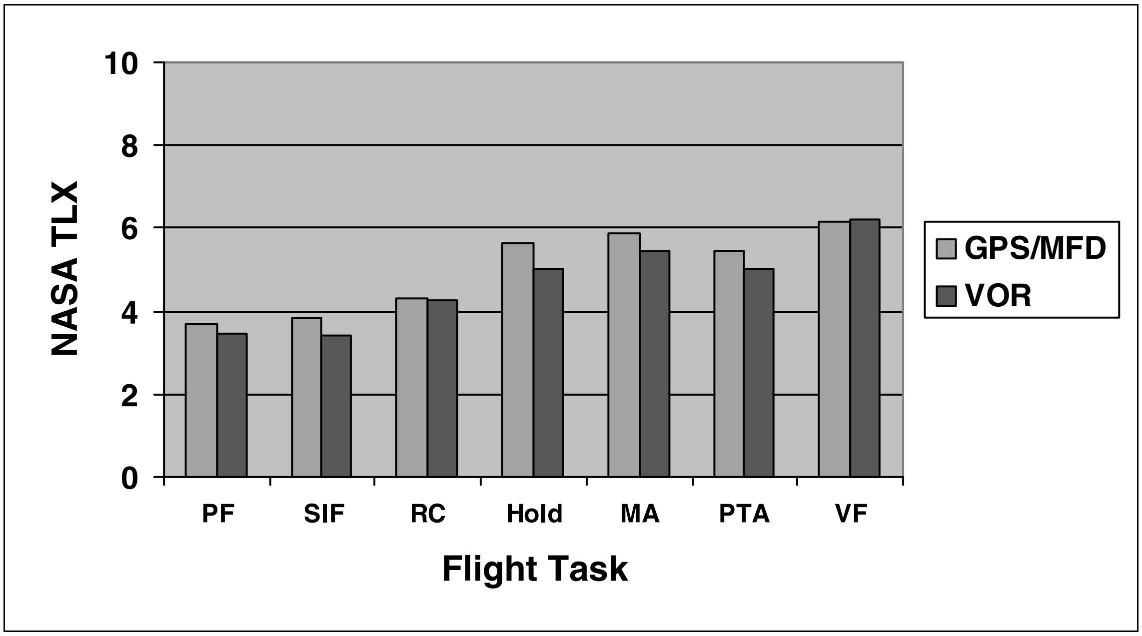

Figure 8: Composite NASA TLX subjective workload estimates, by flight task and display type. PF - Pre-Flight; SIF – Set Initial Frequencies; RC – Route Change; Hold – Holding Procedure; MA – Missed Approach; PTA – Proceed to Alternate; VF – Vacuum Failure.

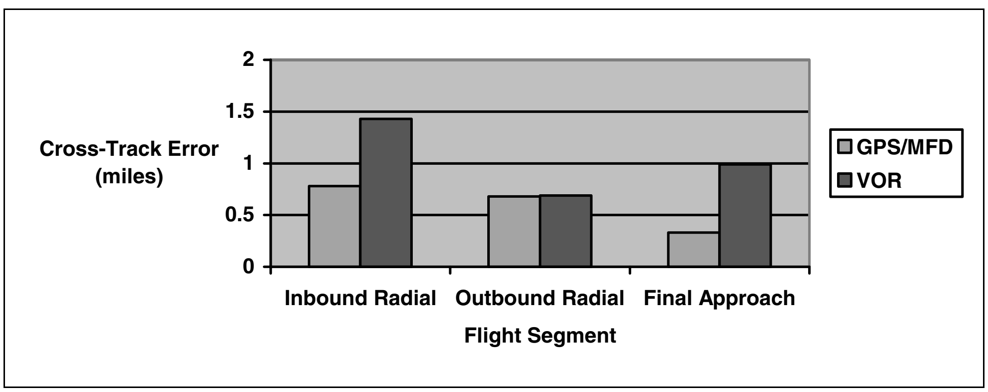

Figure 9: Cross-Track error (in statute miles) by flight segment and display type.

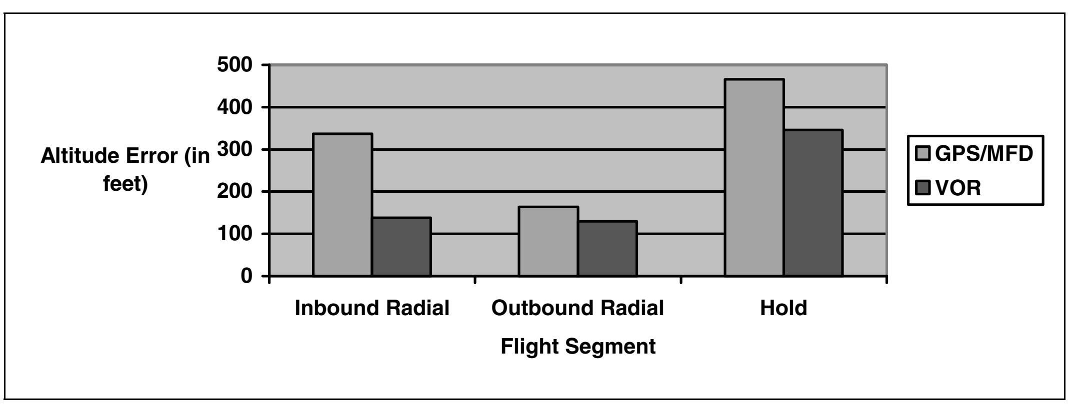

Figure 10: Altitude error (in feet) by flight segment and display type.

shorter than the inbound radial and would have less average error in the signal. However, this explanation does not account for the large differences in cross-track error found for the final approach segment, where factors related to other differences in the displays were most likely involved.

Figure 10 shows the root-mean-square altitude error for three flight segments. The inbound and outbound radial segments are the same as those depicted in Figure 9. The Hold segment occurred while the pilot was flying the holding procedure.

For all three segments, altitude error was less while using the VOR. However, there was a significant difference between display types only for the inbound radial segment, $\underline{t}(15) = 2.22$, $\underline{p} < .05$.

DISCUSSION

As expected, the pilot group recruited for the study varied widely in terms of age (21 - 69 years), total flight experience (145 - 20,000 hours), and most of the other experience variables that were measured (see Table 1). In addition, although 11 (69%) of the pilots had used a GPS unit of some type, only 3 (19%) had ever been exposed to a multi-function display similar to the MX-20. This variability in experience more closely matches the general aviation pilot population than the professional pilot population that has been equipped with these displays as a part of the Capstone Program (Williams et al., 2002).

Results from the usability questionnaire demonstrated that pilots found both the GX-50 and MX-20 units to be usable, without any serious usability problems. The MX-20 received higher usability scores on average than the GX-50, but this was expected because of the simpler design of the MX-20 display. Individual questions about the effects of the MX-20 on situation awareness yielded strong positive responses from the pilots. Indeed, the two highest scores dealt with position awareness using the GPS/MFD relative to standard instruments. This is a particularly important finding, given the documented relationship between pilot situation awareness and flight safety (Endsley, 1995; Endsley, 1997; Roscoe, 1968).

Of the six usability categories listed in the questionnaire, the category receiving the lowest scores for both displays was the effect of the displays on head-down time. It is likely that increased practice and exposure to the displays will decrease the amount of head-down time required to operate the displays. However, observations and interviews of pilots using the system have shown that head-down time can still be a problem for specific functions, such as the display of traffic information, even after years of system use (Williams et al., 2002). Some of the lower scores from the individual items of both the MX-20 and GX-50 usability questions concerned the ability of warnings and alerts to attract attention. This may be because neither of the displays presents auditory annunciations to the pilot, only visual annunciations.

The analysis of pilot interactions with the displays demonstrated that the 2 to 3 hours of training received by the pilots was not enough to conduct the required tasks without committing several errors and requiring assistance from the experimenters. Notably, the pilots produced considerably fewer errors and were given much less assistance when performing MX-20 tasks than when performing GX-50 tasks. This was expected because of the differences in the complexity of the tasks performed, although it is possible that an improved interface design might make the performance of certain GX-50 tasks easier. These results have implications regarding mandatory FAA training requirements for these displays. Perhaps the FAA should consider following the lead of other countries in this matter. Australia, for instance, requires that pilots attend an approved training program, be flight tested, and receive a license endorsement before flying a GPS display in IFR conditions (St. George & Nendick, 1998).

In comparing the effectiveness of the GPS/MFD displays to the standard VOR for conducting instrument flight tasks, several pieces of information are available from the study. First, there were no significant differences between the two display types in terms of the subjective workload estimates given by the pilots. This was somewhat surprising, given the apparent difficulty experienced by many of the pilots in performing the assigned tasks with the GPS/MFD. One possible explanation is that the pilots felt that they could easily master the GPS/MFD displays with practice, which may have affected their estimates.

Despite the lack of a significant difference between subjective workload estimates, performance differences were found between the two display types. For instance, when pilots flew using the GPS/MFD, they were more accurate in terms of cross-track error (horizontal distance from the intended flight path). As mentioned before, this was expected given previous research with moving map displays (Haskell & Wickens, 1993; Roscoe, 1968; Wickens & Prevett, 1995). On the other hand, pilots were less accurate in holding altitude while flying the GPS/MFD, at least during the longest flight segment. A possible explanation for this is that the altimeter was located closer to the VOR display than the GPS/MFD display, making it more difficult for the pilots to include the altimeter in their scan. Although the MX-20 does display altitude information, the pilots were accustomed to looking for altitude information on the altimeter.

The presence of the GPS/MFD after the vacuum failure assisted pilots in maintaining awareness of their position and in improving their horizontal flight path performance during the approach to the runway. Pilots flying the approach on partial-panel instrumentation with only the VOR showed a mean horizontal flight path error of approximately 1 mile. In contrast, when they flew the approach on partial-panel instrumentation with the assistance of the GPS/MFD, their flight path error was approximately $^{1}/_{3}$ of a mile; a dramatic improvement. Subjective estimates further support this finding. Pilots said they felt that it was both easier to control the aircraft and to navigate after the vacuum failure using the GPS/MFD than when using only VOR. These findings also support recent research demonstrating that the presence of a flight instrument within the primary field of view and containing a valid heading reference reduced loss of control of the aircraft while flying partial-panel instrumentation (Beringer & Ball, 2001).

As these new aircraft displays become more common in general aviation cockpits, it is comforting to find evidence of their effectiveness and usability in instrument flight, the most complicated of flight operations. Issues still remain, however. The need for assistance while many of the pilots were interacting with the displays is evidence that training requirements should be modified to specifically address new technology in general aviation cockpits. Also poorly understood is how quickly knowledge of a system is lost if the pilot does not fly for a period of time. The need for assistance also suggests that excessive head-down time could remain a problem when assistance is not available. However, the ability of the MX-20/GX-50 to help the pilot maintain situation awareness, improve navigational accuracy, and increase safety in emergency situations offsets to some extent the additional training that may be necessary or the workload associated with operating the displays.

REFERENCES

Beringer, D.B. & Ball, J.D. (2001). When gauges fail and clouds are tall, we miss the horizon most of all: General Aviation pilot responses to the loss of attitude information in IMC. In *Proceedings of the Human Factors and Ergonomics Society 45th Annual Meeting – 2001*, pp. 21-5.

Endsley, M.R. (1995). A taxonomy of situation awareness errors. In *Human Factors in Aviation Operations*, R. Fuller, N. Johnston, and N. McDonald (Eds.). Aldershot, England: Avebury Aviation, Ashgate Ltd., pp. 287-92.

Endsley, M.R. (1997). Supporting situation awareness in aviation systems. In *Proceedings of the IEEE International Conference on Systems, Man, and Cybernetics*, Orlando, Florida, October 12-15, 1997, pp. 4177-81.

FAA, (2000). US civil airmen statistics. Information available on the Internet at URL http://api.hq.faa.gov/CivilAir/index.htm. Web site of the FAA Office of Aviation Policy and Plans.

FAA, (2003). FAA Alaska Region Home Page. Information available on the internet at URL http://www.alaska.faa.gov/capstone/. Web site of the FAA Alaska Region Capstone Office.

Hart, S.G., & Staveland, L.E. (1988). Development of NASA-TLX (Task Load Index): Results of Empirical, & Theoretical Research. In P.A. Hancock & N. Meshkati (Eds.), *Human Mental Workload,* North-Holland, Amsterdam, The Netherlands: Elsevier Science Pub.

Haskell, I. D. & Wickens, C.D. (1993). Two- and three-dimensional displays for aviation: A theoretical and empirical comparison. *International Journal of Aviation Psychology*, 3(2), 87-109.

Heron, R.M & Nendick, M.D. (1999). Lost in space: Warning, warning, satellite navigation. In D. O'Hare (Ed.), *Human Factors in General Aviation*, (pp. 193-224). Aldershot, UK: Ashgate.

Nendick, M. & St. George, R. (1995). Human factors aspects of global positioning systems (GPS) equipment: A study with New Zealand pilots. In *Proceedings of the Eighth International Symposium on Aviation Psychology* (pp. 152-7). Columbus, OH: The Ohio State University.

Nendick, M. (1995). *Global position satellite system (GPS): Human factors aspects for general aviation pilots*. Unpublished thesis. Massey University: New Zealand.

Roscoe, S.N. (1968). Airborne displays for flight and navigation. *Human Factors*, 13, 561-7.

St. George, R. & Nendick, M. (1998). *GPS training for general aviation VFR pilots: To regulate or educate?* Paper presented at the Fourth Australian Aviation Psychology Symposium, 16-20 March, 1998, Manly, Australia.

Wickens, C. (2000). *Imperfect and unreliable automation and its implications for attention allocation, information access and situational awareness.* Moffett Field CA: NASA Ames Research Center.

Wickens, C.D. & Prevett, T.T. (1995). Exploring the dimensions of egocentricity in aircraft navigation displays. *Journal of Experimental Psychology: Applied*, *1*(2), 110-35.

Williams, K.W. (1999a). *GPS user-interface design problems.* U.S. Department of Transportation, Federal Aviation Administration, Office of Aviation Medicine, Washington, DC. Publication No. DOT/FAA/AM-99/13.[1]

Williams, K.W. (1999b). *GPS user-interface design problems: II*. U.S. Department of Transportation, Federal Aviation Administration, Office of Aviation Medicine, Washington, DC. Publication No. DOT/FAA/AM-99/26.[1]

Williams, K.W., Yost, A., Holland, J., & Tyler, R.R. (2002). *Assessment of advanced cockpit displays for general aviation aircraft – the Capstone Program*. U.S. Department of Transportation, Federal Aviation Administration, Office of Aerospace Medicine, Washington, DC. Publication No. DOT/FAA/AM-02/21.[1]

[1] This publication and all Office of Aerospace Medicine technical reports are available in full-text from the Civil Aerospace Medical Institute's Publications Web site: http://www.cami.jccbi.gov/aam-400A/index.html

APPENDIX A– USABILITY QUESTIONNAIRE

GPS/MFD Full-Mission Usability Study

1. Please rate the usability of each feature in single-pilot IFR operations using the rating scales in the boxes below. For example, for the first feature, choose one of the items numbered 1 – 5 under A, Easy or difficult to use, and write that number in Box A to the right of the first feature description.

A. Effectiveness of Feature/Function 1 = Very ineffective 2 = Moderately ineffective 3 = Borderline effective/ineffective 4 = Moderately effective 5 = Very effective	D. System cues and prompts 1 = Very ineffective 2 = Moderately ineffective 3 = Borderline effective/ineffective 4 = Moderately effective 5 = Very effective
B. Easy or difficult to use 1 = Very difficult 2 = Somewhat difficult 3 = Borderline 4 = Easy to use 5 = Very easy to use	E. System feedback following my actions 1 = Very ineffective 2 = Moderately ineffective 3 = Borderline effective/ineffective 4 = Moderately effective 5 = Very effective
C. Workload 1 = Excessive – Very high 2 = Excessive – Moderately high 3 = Satisfactory – Medium 4 = Satisfactory – Moderately low 5 = Satisfactory – Very low	F. Head down time (Effect on visual scan) 1 = Excessive – Very negative effect on scan 2 = Excessive – Moderately negative effect on scan 3 = Satisfactory – No effect on scan 4 = Satisfactory – Moderately positive effect on scan 5 = Satisfactory – Very positive effect on scan

	Feature Rating Criteria					
Part 1. Multifunction Display	**A**	**B**	**C**	**D**	**E**	**F**
Accessing database information (runway lengths, frequencies, etc)						
Selecting terrain mode						
Map type selection (VFR, IFR, Custom)						
Adjusting altimeter setting						
Map orientation selection (North up, Track up)						
Selection of map data for display – decluttering						
Using navigation data						
Using the map range (zoom) feature						
Using an approach procedure						
Selecting the Pan mode						
Panning the map						
Using map information						
Using terrain information						

Please feel free to write a few words below each of the following items to explain your rating.

1. Overall, the GPS/MFD increased my awareness of nearby terrain relative to conventional instruments.

1	2	3	4	5
Strongly Disagree	Somewhat Disagree	Neither Agree Nor Disagree	Somewhat Agree	Strongly Agree

2. The terrain proximity feature attracted my attention to terrain in a timely fashion.

1	2	3	4	5
Strongly Disagree	Somewhat Disagree	Neither Agree Nor Disagree	Somewhat Agree	Strongly Agree

3. The GPS/MFD increased my awareness of my ground speed, course, and altitude relative to conventional instruments.

1	2	3	4	5
Strongly Disagree	Somewhat Disagree	Neither Agree Nor Disagree	Somewhat Agree	Strongly Agree

4. The GPS/MFD increased my awareness of my position relative to airports, fixes, and airways relative to conventional instruments.

1	2	3	4	5
Strongly Disagree	Somewhat Disagree	Neither Agree Nor Disagree	Somewhat Agree	Strongly Agree

5. The GPS/MFD increased my awareness of my position during instrument approaches relative to conventional instruments.

1	2	3	4	5
Strongly Disagree	Somewhat Disagree	Neither Agree Nor Disagree	Somewhat Agree	Strongly Agree

6. The MFD information I needed was easy to see and not obscured by other information.

1	2	3	4	5
Strongly Disagree	Somewhat Disagree	Neither Agree Nor Disagree	Somewhat Agree	Strongly Agree

7. Text displayed on the MFD was easy to read.

1	2	3	4	5
Strongly Disagree	Somewhat Disagree	Neither Agree Nor Disagree	Somewhat Agree	Strongly Agree

8. The meaning of symbols and text on the MFD was easy to understand.

1	2	3	4	5
Strongly Disagree	Somewhat Disagree	Neither Agree Nor Disagree	Somewhat Agree	Strongly Agree

9. Prompts for pilot inputs, alerts, and advisories effectively attracted my attention.

1	2	3	4	5
Strongly Disagree	Somewhat Disagree	Neither Agree Nor Disagree	Somewhat Agree	Strongly Agree

10. Prompts for pilot inputs, alerts, and advisories were easy to understand.

1	2	3	4	5
Strongly Disagree	Somewhat Disagree	Neither Agree Nor Disagree	Somewhat Agree	Strongly Agree

11. The MFD menus were easy to use.

1	2	3	4	5
Strongly Disagree	Somewhat Disagree	Neither Agree Nor Disagree	Somewhat Agree	Strongly Agree

12. The MFD menu options were easy to understand.

1	2	3	4	5
Strongly Disagree	Somewhat Disagree	Neither Agree Nor Disagree	Somewhat Agree	Strongly Agree

13. The MFD button labels were easy to understand.

1	2	3	4	5
Strongly Disagree	Somewhat Disagree	Neither Agree Nor Disagree	Somewhat Agree	Strongly Agree

14. Information about fixes shown on the MFD maps was easy to obtain.

1	2	3	4	5
Strongly Disagree	Somewhat Disagree	Neither Agree Nor Disagree	Somewhat Agree	Strongly Agree

15. The use of colors on the MFD maps was meaningful.

1	2	3	4	5
Strongly Disagree	Somewhat Disagree	Neither Agree Nor Disagree	Somewhat Agree	Strongly Agree

16. I remained geographically oriented while I changed heading.

1	2	3	4	5
Strongly Disagree	Somewhat Disagree	Neither Agree Nor Disagree	Somewhat Agree	Strongly Agree

17. I remained aware of ownship position when I panned the MFD map.

1	2	3	4	5
Strongly Disagree	Somewhat Disagree	Neither Agree Nor Disagree	Somewhat Agree	Strongly Agree

18. The size of the MFD display area was adequate for the information presented.

1	2	3	4	5
Strongly Disagree	Somewhat Disagree	Neither Agree Nor Disagree	Somewhat Agree	Strongly Agree

19. Did you make any errors in using the MFD (any misinterpretations of displayed information, or anything you did incorrectly or omitted)? Yes No

    If so, please describe the error(s) as well as the cause and consequences of those errors:

A. Effectiveness of Feature/Function 1 = Very ineffective 2 = Moderately ineffective 3 = Borderline effective/ineffective 4 = Moderately effective 5 = Very effective	D. System cues and prompts 1 = Very ineffective 2 = Moderately ineffective 3 = Borderline effective/ineffective 4 = Moderately effective 5 = Very effective
B. Easy or difficult to use 1 = Very difficult 2 = Somewhat difficult 3 = Borderline 4 = Easy to use 5 = Very easy to use	E. System feedback following my actions 1 = Very ineffective 2 = Moderately ineffective 3 = Borderline effective/ineffective 4 = Moderately effective 5 = Very effective
C. Workload 1 = Excessive – Very high 2 = Excessive – Moderately high 3 = Satisfactory – Medium 4 = Satisfactory – Moderately low 5 = Satisfactory – Very low	F. Head down time (Effect on visual scan) 1 = Excessive – Very negative effect on scan 2 = Excessive – Moderately negative effect on scan 3 = Satisfactory – No effect on scan 4 = Satisfactory – Moderately positive effect on scan 5 = Satisfactory – Very positive effect on scan

Part 2. GPS Navigator	**A**	**B**	**C**	**D**	**E**	**F**
Accessing database information (runway lengths, frequencies, etc)						
Entering flight plans						
Editing flight plans						
Selecting “Direct To” function						
Using GPS navigator to fly a radial to/from a waypoint						
Using GPS navigator to fly a holding pattern						
Loading and flying GPS approaches						
Using the CDI data						
Using cross-track error (XTE) data						
Using DTK data						
Using Message information						
Accessing flight plan leg information						
Using the Nearest (airport) function						

Please feel free to write a few words below each of the following items to explain your rating.

20. It was easy to enter data into the GPS receiver.

1	2	3	4	5
Strongly Disagree	Somewhat Disagree	Neither Agree Nor Disagree	Somewhat Agree	Strongly Agree

21. The knobs and buttons on the GPS receiver were placed in logical and convenient locations.

1	2	3	4	5
Strongly Disagree	Somewhat Disagree	Neither Agree Nor Disagree	Somewhat Agree	Strongly Agree

22. The GPS receiver controls for different functions operate in a consistent manner.

1	2	3	4	5
Strongly Disagree	Somewhat Disagree	Neither Agree Nor Disagree	Somewhat Agree	Strongly Agree

23. Text on the GPS display was easy to read.

1	2	3	4	5
Strongly Disagree	Somewhat Disagree	Neither Agree Nor Disagree	Somewhat Agree	Strongly Agree

24. The size of the GPS display area was adequate for the information displayed.

1	2	3	4	5
Strongly Disagree	Somewhat Disagree	Neither Agree Nor Disagree	Somewhat Agree	Strongly Agree

25. It was easy to select GPS information (airports, airport information, VORs, waypoints, etc.).

1	2	3	4	5
Strongly Disagree	Somewhat Disagree	Neither Agree Nor Disagree	Somewhat Agree	Strongly Agree

26. It was easy to select a GPS approach.

1	2	3	4	5
Strongly Disagree	Somewhat Disagree	Neither Agree Nor Disagree	Somewhat Agree	Strongly Agree

27. GPS warnings and alerts were issued at the right time.

1	2	3	4	5
Strongly Disagree	Somewhat Disagree	Neither Agree Nor Disagree	Somewhat Agree	Strongly Agree

28. GPS warnings and alerts effectively attracted my attention.

1	2	3	4	5
Strongly Disagree	Somewhat Disagree	Neither Agree Nor Disagree	Somewhat Agree	Strongly Agree

29. It was easy to control the airplane after the vacuum failure using the MFD/GPS.

1	2	3	4	5
Strongly Disagree	Somewhat Disagree	Neither Agree Nor Disagree	Somewhat Agree	Strongly Agree

30. It was easy to control the airplane after the vacuum failure using only conventional instruments.

1	2	3	4	5
Strongly Disagree	Somewhat Disagree	Neither Agree Nor Disagree	Somewhat Agree	Strongly Agree

31. It was easy to navigate after the vacuum failure using the MFD/GPS.

1	2	3	4	5
Strongly Disagree	Somewhat Disagree	Neither Agree Nor Disagree	Somewhat Agree	Strongly Agree

32. It was easy to navigate after the vacuum failure using only conventional instruments.

1	2	3	4	5
Strongly Disagree	Somewhat Disagree	Neither Agree Nor Disagree	Somewhat Agree	Strongly Agree

33. Did you make any errors in using the GPS (any misinterpretations of displayed information, or anything you did incorrectly or omitted)? Yes No

    If so, please describe the error(s) as well as the cause and consequences of those errors: