DIFFERENCES IN IN-FLIGHT UNUSUAL ATTITUDE RECOVERY PERFORMANCE AND WORKLOAD

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ABSTRACT
A critical use of Primary Flight Displays (PFDs) is Unusual Attitude Recovery (UAR). Due to cost and safety considerations, very little in-flight data exist for UARs and even less for UARs in transport category aircraft. This paper describes such UAR performance data. Specifically as part of an in-flight evaluation of proposed upgrades to the C-141 PFDs, UARs were performed in the Air Force Total In-Flight Simulator (TIFS) aircraft. The UAR task consisted of an automatic set-up maneuver followed by manual recovery. Initial conditions varied from +15 to -20 degrees pitch attitude combined with +45 to -60 degree roll attitude at 1800 or 230 KIAS. The participants were four current C-141 Air Force pilots and two current Air Force test pilots. Each flew five sorties. The first sortie was for training followed by four sorties for data collection. The training sortie followed a profile similar to that of a data flight but the TIFS crew interacted with the participant to ensure that the participant was fully cognizant of the test conditions, operational test procedures, and the test and data objectives. Two of the four data flights were used to evaluate one of the display configurations (current baseline or proposed upgrade). Five years after the initial data collection, the objective data from the UARs were analyzed using multivariate analysis of variance (MANOVA) as a function UAR and pilot. The dependent variables were aircraft state during the recovery, reaction times (RTs), percent correct control inputs, recovery time, pitch controller movement, roll controller movement, throttle movement, and SWAT ratings. There was a significant effect of pilot on aircraft state, reaction time, percent correct control inputs, recovery time, pitch control movement, roll control movement, and SWAT rating. There was a significant UAR effect for the two nose-high UAR initial conditions: the percent correct of pitch inputs was significantly less than that exhibited for the nose-low UAR conditions.

INTRODUCTION
Although spatial disorientation has been a causal factor in hundreds of military and civilian aircraft accidents, very few in-flight studies have been performed in unusual attitude recovery. Typically, research on spatial disorientation countermeasures, such as display symbology, has been conducted in simulators (e.g., Beringer, Ball, Brennan, and Taite, 2004; Guttman, 1986) although there have been several small General Aviation Aircraft flight tests (e.g., Piper Saratoga used in Poonawalla, Pandya, Kephart, and Braasch, 2006 and a Piper Cheyenne I Super 500 used in Schiefele, Howland, Maris, and Wipplinger, 2004)

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METHOD

Participants

There were six participants in this study. The four C-141 line pilots had almost exclusively C-141-only flight time (1500 to 3000 hours). The C-141 line pilot previous exposure to glass cockpit displays and "advanced" display systems was minimal. The two test pilots had the least amount of in-type flight time (< 100 hours) but had comparable flight times (2800 to 3500 hours). Two subjects were Majors (Rank O-4), three were Captains (Rank O-3), and one was a Lieutenant (Rank O-2).

Test Aircraft

The TIFS was a highly modified C-131 (Convair 580), owned by the US Air Force, configured as a six degree-of-freedom simulator (Figure 1). General Dynamics (formerly, Calspan) modified and operated the TIFS aircraft during this data collection period. TIFS had a separate simulation cockpit forward and below the normal C-131 cockpit. When flown from the simulation cockpit in the simulation mode, the participant’s control commands were fed as inputs to onboard computers which calculated the aircraft response to be simulated (in this case, the C-141 aircraft). These responses, along with TIFS motion sensor signals, were used to generate feed forward and response error feedback signals in an explicit model-following simulation, which drove the six controllers on the TIFS. The six TIFS controllers - ailerons, rudder, elevator, throttle, side force surfaces, and direct lift flaps - provided independent control of all six degrees-of-freedom. The result was a high-fidelity reproduction of the motion cues at the pilot position of the simulated aircraft.

Figure 1. USAF Total In-flight Simulator (TIFS) Aircraft
Safe flight operations were maintained through a "safety trip system." The left-hand side of the TIFS aircraft was configured to resemble the C-141 aircraft albeit only to the extent necessary to evaluate the proposed PFD/ND formats against the baseline, current C-141 PFR instrumentation. A wheel-column and rudder pedals were installed and calibrated to produce the same control force and displacement characteristics of the C-141 aircraft. The evaluation cockpit instrument panel was modified to include the proposed upgraded displays and a 25” (diagonal) monitor was installed forward of the evaluation pilot. The monitor was driven from the output of a Silicon Graphics, Inc computer (using an SXGA format with 1280x1024 pixel resolution) which simulated the proposed C-141 cockpit upgraded displays as well as the current baseline PFR instrumentation.

**Tasks**

Three evaluation tasks were conducted to gather data regarding the safety-of-flight and usability of the proposed C-141 PFR display upgrade: 1) Unusual Attitude Recovery (UAR), 2) Instrument Landing System (ILS) approach, and 3) Precision Instrument Control Task (PICT). All tasks were flown under simulated Instrument Meteorological Conditions (IMC) using outside vision which consisted of opaque black drapes and canopy masking the inside of the evaluation cockpit. Half of the flights for each participant were flown with the current C-141 PFR instrumentation. Two test conditions were flown: 1) up-and-away flight between 5000 and 10,000 feet Mean Sea Level and 2) power approach. In up-and-away flight, the UARs, PICT, and a simulated ILS were flown. In power-approach flight, an actual ILS returning to base at the Greater Buffalo International Airport was flown. Only the results for the first task, UAR, are described here.

**UAR**

The UAR task consisted of an automatic set-up maneuver followed by manual subject recovery. To set-up the UAR, the TIFS automatically flew a pre-programmed "masking" maneuver through the model-following system. The maneuver hid the UAR initial condition (IC) which was a predefined target attitude (pitch and bank angle) and airspeed (Table 1). The masking maneuver was similar for each UAR set-ups. The masking maneuver lasted 15 to 25 seconds and terminated at the desired IC.

**Table 1. Unusual Attitude Initial Conditions**

<table>
<thead>
<tr>
<th>UAR Number</th>
<th>Initial Flight Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pitch Attitude (deg)</td>
</tr>
<tr>
<td>1</td>
<td>+15</td>
</tr>
<tr>
<td>2</td>
<td>+15</td>
</tr>
<tr>
<td>3</td>
<td>-10</td>
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<tr>
<td>4</td>
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<td>5</td>
<td>-10</td>
</tr>
<tr>
<td>6</td>
<td>-20</td>
</tr>
</tbody>
</table>
To initiate the task, the simulation system was engaged and the participant made a quick controllability check. Once ready, the participant was told to guard the stick and throttles. The participant instrument display changed to an all black display with "UAR" printed in the center to provide a foveal target at the proper focal point. The participant’s controls stayed in their trimmed, neutral position. Once the IC was reached, the participant's instruments were activated to the actual flight conditions and a distinctive two-second tone was transmitted over the intercom, thus, cueing the participant to initiate recovery.

Procedures for the UARs were briefed to each participant. The briefed recovery procedures were consistent with standard AFM 51-37 procedures. However, since specific recovery procedures are only generally defined in AFM 51-37 for transport-type aircraft, more "formalized" recovery procedures were used to support quantitative analysis of UAR inputs. The participants were trained during ground simulations on these recovery procedures. For nose-high UARs, the participants were instructed to roll in the shortest direction to 45 degrees of bank, allow the nose to "slice" to the horizon, and recover to wings level. For nose-low UARs, the participants were instructed to roll wings-level and "pull" to the horizon. Throttles should be advanced for nose-high attitude ICs; conversely, throttles should be retarded for nose-low attitude ICs. The UAR scoring parameters were also briefed. The time to identify the UAR and initiate correct pitch, roll, and thrust inputs was graded, in addition to the "correctness" of the recovery inputs. Time to recover to wings-level was not graded so excessive 'g' was not to be used. Normal acceleration between 1.5 and 2.0 g was expected in the recovery.

Pilot recovery performance for the eight UARs were “scored” (i.e., correct or incorrect) based on the direction of control input in accordance to the UAR procedures (Table 2). Determination of UAR "correctness" was made by comparing the control input time histories to the recovery criteria. After the tone was initiated, the participant’s control inputs (wheel/column pitch and roll deflection and throttle handle displacement) were examined. Participant’s control inputs were identified as "significant" if they exceeded threshold values. The threshold values were: 0.30 inches of pitch controller deflection, 2 degrees of roll controller deflection, and 2 degrees of throttle handle displacement from trim. (Note, full-scale deflection of the controllers was: +7 inches, -5 inches for pitch, ±90 degrees for roll, and +80 to +29 degrees for throttle.) The time of these inputs and their direction were noted. When grading the UAR, a "1" signified a correct input and a "0" signified an incorrect input. For example, if the significant roll input was in the direction of a left roll in UAR Number 1, the "score" was incorrect (i.e., the participant initially put in roll control in the wrong direction to recover). Subsequent corrected inputs were not scored. The UAR was completed once the participant established wings-level flight with a flight path angle (FPA) of ±5 degrees for 5 seconds.

<table>
<thead>
<tr>
<th>UAR Number</th>
<th>Initial Flight Condition</th>
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<tbody>
<tr>
<td></td>
<td>Pitch Attitude (deg)</td>
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<td>7</td>
<td>-20</td>
</tr>
<tr>
<td>8</td>
<td>-20</td>
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</table>
Table 2. UAR Initial Conditions and Recovery Input Scores

<table>
<thead>
<tr>
<th>UAR No.</th>
<th>Pitch Att. (deg)</th>
<th>Roll Att. (deg)</th>
<th>Air-speed KIAS</th>
<th>Left</th>
<th>None</th>
<th>Right</th>
<th>Fwd</th>
<th>None</th>
<th>Aft</th>
<th>Mil</th>
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<td>1</td>
<td>0</td>
<td>0</td>
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<td>230</td>
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<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
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<tr>
<td>4</td>
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<td>230</td>
<td>0</td>
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<td>1</td>
<td>0</td>
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<td>1</td>
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All eight UARs were conducted on each flight. Thus, each UAR was conducted 4 times by each participant, over the course of the flight test (2 UARs for each display configuration). For the UAR task analysis, the following objective data were measured:

- pitch, roll, and throttle controller reaction times (i.e., the elapsed time for controller input to exceed threshold values)
- correct /incorrect score for each controller input (see table 2)
- time to complete the UAR and altitude loss/gain
- shortest reaction time and type
- shortest correct reaction time and type
- control input statistics in the recovery (i.e., mean, variance, standard deviation, maximum, and minimum values of pitch, roll, and throttle control inputs).

The subjective questionnaire for this task, with bipolar rating scales, was completed immediately after finishing each UAR.

**Training**

All participants were trained before flight-testing. This training included: 1) egress training for the TIFS aircraft; 2) required operations in the TIFS evaluation cockpit (i.e., location of instrument power switches, operation of intercom, piloting controls, and safety equipment); 3) familiarity in TIFS operating procedures; and 4) training in the evaluation tasks. All training was conducted hands-on using the TIFS ground-simulation mode of operation. In this mode, all TIFS systems were operated as they would in-flight with the primary exception that the TIFS motions were not present.
**Test Procedures**

A pre-flight briefing was conducted before each flight. The participants were briefed on which tasks that they were to accomplish. However, the test conditions were not revealed (e.g., the participant was not aware of the UAR ICs). Each participant flew five sorties. The first sortie was for training followed by four sorties for data collection. The training sortie followed a profile similar to that of a data flight but the TIFS crew interacted with the participant to ensure that the participant was fully cognizant of the test conditions, operational test procedures, and the test and data objectives. Two of the four data flights were used to evaluate one of the display configurations (current baseline or proposed upgrade). On each sortie, the participant flew four evaluation tasks during the up-and-away portion. These consisted of two simulated ILS tasks from the group of condition sets, a UAR task set, and a PICT.

**RESULTS**

The independent variables for the TIFS flight-testing were the display configuration (current or proposed C-141 display configuration), flight task, and participant. The test was a repeated-measures factorial design. Evaluation tasks and display type were counterbalanced to eliminate training and fatigue effects. Only the results for the UAR task are reported here. The objective data from the UARs were analyzed using multivariate analysis of variance (MANOVA) as a function UAR, pilot, and display. Display effects are described in Bailey, Gawron, and Priest (1994) and Gawron and Bailey (1995). The dependent variables were aircraft state during the recovery, reaction times (RTs), percent correct control inputs, recovery time, pitch controller movement, roll controller movement, throttle movement, and SWAT. The results for each of these types of dependent variables are described in a separate section below.

**Aircraft State**

There was a significant main effect of pilot (Hotellings T (25, 497) = 0.807, p = 0.000) for only two of the five aircraft state measures: pitch attitude (p = 0.001) and vertical flight path angle (p < 0.000) with pilot 1 having the largest negative degrees in both (see Figure 2). The interaction between UAR and pilot was not significant (Hotellings T (175, 497) = 1.663, p = 0.668).
A second MANOVA was calculated for RTs as a function of UAR, pilot, and display. There was no significant difference for UAR (Hotellings T (35, 407) = 0.218, p = 0.992). There was a significant effect of pilot, however (Hotellings T (25, 407) = 8.760, p = 0.000) for all five RTs (p < 0.000 for each). Pilot 1 had the longest pitch RT, Pilot 5 the shortest (see Figure 3). The same results occurred for roll RT, throttle RT, and fastest correct RT. Pilot 1 had the longest incorrect RT; Pilot 2 had the shortest. The interaction of UAR and pilot was not significant (Hotellings T (140, 407) = 5.468, p = 0.000).

**Reaction Times**

Figure 2. Effect of Pilot on Aircraft Pitch
A third MANOVA was calculated for display, UAR, and pilot. The dependent variables were percent correct pitch, roll, and throttle control inputs. The results for display are described in Bailey, Gawron, and Priest (1994) and Gawron and Bailey (1995). There was a significant UAR effect (Hotellings T (21, 305) = 7.352, p = 0.000) as well as for pitch (p < 0.000), roll (p = 0.001), and throttle (p = 0.017). As seen in Figure 4, for the two nose-high UAR initial conditions (UAR 1 and 2), the percent correct of pitch inputs was significantly less than that exhibited for the nose-low UAR conditions.
There was also a significant pilot effect (Hotellings T (15, 305) = 2.539, p = 0.000) as well as for pitch (p = 0.030), roll (p = 0.019), and throttle (p < 0.000) (see Figure 5).

**Figure 5. Interactive Effect of Pilot and Control on Percent Correct Control Inputs**

There was also a significant interactive effect (Hotellings T (105, 305) = 1.807, p = 0.000) for two of the dependent variables (pitch (p = 0.004, Figure 6) and roll (p = 0.006), Figure 7). UARs 1 and 2 showed the greatest differences in percent correct control inputs.

**Figure 6. Interactive Effect of UAR and Pilot on Percent Correct Roll Inputs**
A univariate analysis of variance (ANOVA) was calculated for display, UAR, and pilot for recovery time. There was no significant main effect for UAR ($F(7, 103) = 1.231, p = 0.293$). There was, however, a significant effect of pilot ($F(5, 103) = 8.587, p = 0.000$) with recovery times more than twice as long for the slowest pilot than for the fastest pilot (see Figure 8). The interaction of UAR and pilot was not significant.
**Pitch Control Movement**

A fourth MANOVA was calculated for pitch control movement as a function of display, UAR, and pilot. There was a significant UAR effect (Hotellings $T (35, 497) = 2.854, p = 0.000$) for all five measures (all $p < 0.000$ except minimum $p = 0.001$). However, while the means were statistically different, they were not practically different and their values were near zero. Hence, only the maximum, minimum, and variance (see Figure 9) statistics will be discussed as relevant measures to the UAR task analysis.

![Figure 9. Effect of UAR on Maximum and Minimum Pitch Control Movement](image)

There was also a significant effect of pilot (Hotellings $T (25, 497) = 2.115, p = 0.000$) for all three relevant dependent variables (maximum and variance $p < 0.000$, minimum $p = 0.006$, see Figure 10).

![Figure 10. Main Effect of Pilot on Pitch Control](image)
There was a significant UAR by pilot interaction (Hotellings T (175, 497) = 2.433, p = 0.004) but only for two of the three relevant elevator measures (maximum p = 0.042, variance p = 0.014, Figures 11 and 12).

![Interactive Effect of UAR and Pilot on Maximum Pitch Control Movement](image1)

**Figure 11.** Interactive Effect of UAR and Pilot on Maximum Pitch Control Movement

![Interactive Effect of UAR and Pilot on Variance Pitch Control Movement](image2)

**Figure 12.** Interactive Effect of UAR and Pilot on Variance Pitch Control Movement
Roll Control Movement

A fifth MANOVA was calculated for roll control measures as a function of display, UAR, and pilot. There was a significant UAR effect (Hotellings T (35, 492) = 19.822, p = 0.000) for all five measures (p < 0.000). As with the pitch analysis, the means may have been statistically different, but they were not practically significant so the minimum, maximum, and variance are shown in Figure 13.

![Figure 13. Effect of UAR on Roll Control Movement](image)

There was also a main effect of pilot (Hotellings T (25, 292) = 3.578, p = 0.000; maximum and variance p < 0.000, minimum p = 0.001, see Figure 14).

![Figure 14. Effect of Pilot on Roll Control Movement](image)
There was also a significant UAR by pilot interaction (Hotellings T $T(175, 492) = 4.502$, p $= 0.000$) on all aileron measures (maximum, standard deviation, add variance p $< 0.000$, mean p $= 0.009$, minimum p $= 0.016$, see Figures 15, 16, 17, 18, and 19).

**Figure 15. Interactive Effect of UAR and Pilot on Maximum Roll Control Position**

**Figure 16. Interactive Effect of UAR and Pilot on Mean Roll Control Position**
Figure 17. Interactive Effect of UAR and Pilot on Minimum Roll Control Position

Figure 18. Interactive Effect of UAR and Pilot on Standard Deviation Roll Control Position
A sixth MANOVA was calculated for throttle position. There was a significant UAR effect (Hotellings T (35, 647) = 2.411, p = 0.000) for three of the five variables (maximum and mean p < 0.000, minimum p < 0.003, see Figure 20). There were no other significant effects on throttle position. Again, the mean values may be statistically different, but they are not practically significant.
**SWAT**

An ANOVA was calculated for SWAT as a function of display, UAR, and pilot. There were significant main and interactive effects (see Table 3 and Figure 21).

<table>
<thead>
<tr>
<th>Variable</th>
<th>Sum of Square</th>
<th>DF</th>
<th>F</th>
<th>P</th>
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</tr>
<tr>
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<td>9,779.102</td>
<td>0.000</td>
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<tr>
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</tr>
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</table>

**Table 3. Source Table for SWAT as a Function of UAR and Pilot**

![Figure 21. Interactive Effect of UAR and Pilot on SWAT Rating](image)

**Discussion**

The objective dependent data from the UARs flown in an evaluation of current and proposed upgraded PFR displays for the C-141 aircraft were analyzed as a function UAR and pilot, collapsing across display configuration. Display effects are described in Bailey, Gawron, and Priest (1994) and Gawron and Bailey (1995). These analyses are presented to highlight differences that can be expected in testing of unusual attitude recovery performance and to capture lessons-learned.
The dependent variables were aircraft state data during the recovery, reaction times (RTs), percent correct control inputs, recovery time, pilot control input motion (pitch controller, roll controller, and throttle movement), and subjective workload (as measured by SWAT).

**Aircraft State**

Analysis of aircraft state data showed several statistically significant differences. However, while significant, these data merely quantify the various UAR initial conditions used. Statistical differences are also shown between pilots but, while statistically different, these differences are not practically significant. It is critical in UAR testing to: a) include masking maneuvers and other experimental procedures to limit awareness and foreknowledge of the ultimate UAR initial condition to prevent data contamination; and b) provide a wide cross-section of attitudes and aircraft states appropriate to the aircraft class. With these design steps in place, the analysis of aircraft state data does not provide any indication of unusual attitude recovery performance as recovery differences, if any manifest themselves in the aircraft state data, are hidden in the large numerical differences created by the UAR initial conditions. Attempts to normalize the aircraft state data in an attempt to highlight recovery performance differences were not tried because of minimal expectations given the typical variations in state data found in flight testing.

**Reaction Time**

The analysis of reaction time data showed intuitive results from UAR testing. Statistically significant individual pilot reaction time differences were found. These individual pilot differences were consistent across all controllers indicative of consistency in pilot control technique. Roll control reaction times were the shortest for each pilot since roll control is almost universally the most critical axis in recovery from unusual attitudes (i.e., the aircraft lift vector has to be pointed in the correct direction before pitch correction will be effective). Further, no reaction time differences were noted across UAR conditions; thus, the pilots reacted in the same manner independent of the initial attitude. This implies that the UAR initial conditions (and the resulting display depictions) equally conveyed a sense of urgency to recover for the pilots.

**Percent Correct Control Inputs**

Analysis of percent correct control input data shows results indicative of the test design and typical of individual piloting differences. The nose-high unusual attitude conditions showed significantly worse percent correct scores, particularly in pitch, compared to the nose-low unusual attitude initial conditions. The incorrect scores occurred because the pilots of transport aircraft were reluctant to use forward pitch inputs and potentially unload the aircraft (which would upset cargo or passengers). The preferred recovery procedure for the pilots was to use roll control to enable the aircraft to slice back to the horizon. In hindsight, the recovery scores for pitch in UAR1 and UAR2 should have probably allowed no pitch input to be scored a “correct” recovery input. While this was considered before the flight test, subject matter experts in pre-testing considered “no pitch control input” to be incorrect. In fighter aircraft UAR testing, this issue is not a problem because correct recovery procedures for fighter aircraft are clear-cut in that pilots are trained to roll inverted and pull to the horizon.

It may have been possible to achieve better recovery scores by having more severe nose-high unusual attitudes; that is, given extreme nose high conditions, pilots would be less reluctant
to push over the aircraft (i.e., “unload”) if their energy state was critically depleting, but safety of flight considerations for this test did not permit higher pitch attitudes than 15 degrees nose-up.

**Recovery Time**

Analysis of recovery time data showed results indicative of the test design and individual piloting differences that should be expected. The time to recovery statistically varied between pilots. Recovery time depended upon the pilot technique each pilot used – some intentionally overshooting the straight-and-level recovered position to ensure positive recovery. Recovery time also depended upon their willingness to use significant positive gs in the recovery. Some pilots were more cautious in using positive gs and did not want to overshoot the desired recovery g-load whereas others were not as cautious. This pilot attitude was also affected by the UAR condition and the pilot’s perception of the aircraft energy state and its rate of change. All pilots were willing to maneuver the aircraft as necessary but often felt a recovery was underway and it was not necessary to rapidly recover. In pre-flight instructions, the pilots were not instructed to recover as quickly as possible. The main influence of the primary flight instrumentation design occurs in the initial unusual attitude recognition and initial recovery response - not in the pilot’s ability to control the aircraft during the recovery.

The UAR condition also dictated recovery time as the nose-high conditions are converging toward a recovered energy state; thus, recovery time was rapid whereas the nose-low conditions are diverging necessitating more time to recovery.

**Control Effector Movement**

Analysis of pilot pitch control movement data again showed dependency on the pilot and UAR initial condition. The least severe UAR condition showed the smallest pitch control input movement statistics although the practical differences for pitch control inputs across pilot and UAR are minimal. Pitch control was not the critical control axis.

Statistical pilot roll control movement differences are shown for variance across the UAR initial conditions. Interesting, these data showed that the nose-high UARs exhibit more roll control movements (higher variance) but this result was a statistically anomaly. The pilots commented of the critical need to get the roll attitude of the aircraft to the wings-level condition in the nose-low conditions to effect a proper and quick recovery. Very large and abrupt roll control inputs were used accordingly. However, the more severe nose-low conditions typically were of a longer time duration where little roll control input was necessary once the pilots had rolled to near wings-level conditions; thus, the roll control input variance statistic showed small numerical values which did not reflect the critical initial responses of the pilot. Capturing these initial control input responses, rather than using the entire recovery time period should be used in the future. Individual differences in roll control movement data were expected and were indicated in the data analysis.

**Workload**

Analysis of subjective pilot workload data, as measured by SWAT, showed significant individual pilot differences and differences due to the UAR initial conditions. These data were not unexpected. The UAR initial conditions elicited different levels of workload for each individual pilot. Further, the subjective workload varied by individual. Some pilots felt the UARs required more workload than others. Whether SWAT was the proper measure to capture
the physical and mental stresses associated with unusual attitude recognition and recover was not
tested but should be explored.

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