Workload Assessment of a Trajectory Guidance Display

Barbara A. Bernabe
*Florida Institute of Technology, School of Psychology, Melbourne, Florida*

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ABSTRACT
The present study evaluated the utility of a Flight Test Trajectory controller, a special purpose display, in improving pilot performance and reducing workload during difficult test maneuvers. Algorithmic controlled indicators presented focally and in an integrated manner, information about pitch and roll stick control and Mach error. The display thus functioned as a flight guidance system, with the pilot's task being to reduce the error signal.

In two simulated maneuvers, performance, as measured by time to achieve condition and elapsed time on condition, was facilitated by the trajectory controller when compared with performance using conventional instrumentation. In addition, pilot workload, measured by performance on two secondary tasks was significantly reduced in the trajectory display condition.

DISPLAY COMPONENTS
The components of the guidance system are illustrated in Figure 1. The display consists of horizontal and vertical crossbars which appear similar to glideslope/localizer needles, and a side pointer. The indicators are driven by algorithms which compare current vehicle state with signals to the pilot, in the form of deviation of indicator components from the center of the display. The horizontal and vertical needles provide pitch and roll stick control information respectively, while the side pointer provides throttle information. Errors are damped by following each of the indicator needles with control stick movements. Thus, all needles function as fly to commands, and the pilot's task essentially becomes one of tracking and centering the indicators with stick and thrust control commands.
EXPERIMENTAL TEST

A simulator study was conducted to test the display in facilitating pilot performance in flight test maneuvers. Both flying performance and pilot workload were selected as measures of display effectiveness.

Workload and performance, although related, are assumed to be independent measurement factors. While workload is considered to be the amount of effort required by task demands (Kahneman, 1973), observed performance will depend on the degree of saturation of limited cognitive resources. Thus, two tasks which differ in overall workload required may result in similar primary task performance measures if attentional capacity is not completely saturated by the tasks, (Hart, 1980). Workload differences are expected, however, to result in unequal amounts of "residual attention", that is the capacity to perform effectively in tasks other than the primary task (Roscoe, 1980).

Primary flying task performance consisted of measuring time to achieve the test condition and the duration spent "on condition" for two typical flight test maneuvers, a level turn and a Ps=0. Workload was measured by testing performance on two kinds of secondary tasks, simple reaction time and time estimation. Simple reaction time was assumed to tap residual perceptual capacity, i.e., the ability to detect a signal not directly related to the primary task. Time estimation was assumed to tap residual attentional capacity, since accurate performance required a pilot to continuously monitor elapsed time (Hart, 1980). It was predicted that the display would facilitate performance on flying the test maneuvers, and that by reducing perceptual and cognitive workload would also lead to superior performance on the two secondary tasks.

METHOD

Subjects. Four experimental subjects participated in the present study. All were volunteers from the Air Force Test Pilot School at Edwards Air Force Base, and all were familiar with the test flight maneuvers.

Apparatus. The experiment was conducted at NASA Dryden Research Facility in an engineering simulator fully configured to respond like an F-15, and equipped with a conventional F-15 instrument panel. For the experimental conditions the panel was modified to include the special purpose display superimposed over the altitude indicator. A red light, as the signal for reaction time responses, was attached to the instrument panel to the left of the altitude indicator. A Modcomp computer controlled all simulator functions and reaction time signals, and calculated dependent measures. An illustration of simulator cockpit layout is presented in Figure 2.

Design and Procedure. In a 2 x 2 x 2 within subject design, each subject was required to fly two maneuvers, a level turn and a Ps=0, with and without the display, and with and without the secondary task. Test points for each maneuver are presented in Table 1. Each maneuver was initiated five hundred feet below altitude and pilots were required to climb to test altitude. Performance data for each condition was collected on three, seventy-five second runs, each of which was preceded by five practice trials. Primary task performance data was measured quantitatively by calculating the amount of time required to achieve the specified test condition and the amount of time elapsed on condition for three sets of tolerances, course, intermediate, and fine. Tolerance limits are presented in Table 2. Pilot control stick-error for each parameter of the test condition was recorded as a qualitative performance measure. In addition a summed error over all parameters was computed and also recorded on strip charts. For the qualitative measures, error tolerances were based on intermediate limits.

Secondary tasks were of two kinds. One consisted of simple reaction time to a cockpit light situated to the left of the altitude indicator. Reaction time was measured from the onset of the light to the time the trigger on the control stick was depressed. The other task consisted of estimating a ten second interval. Each estimate started from the time the trigger was depressed and ended when the pilot depressed the trigger a second time. Dependent measures of the time estimation task were mean deviation from baseline estimates and the variability of time estimates as computed by absolute deviation*. Dependent measures for primary and secondary tasks are outlined in Table 3.

In order to collect baseline data ten reaction time and time estimation trials were run prior to practice trials while the pilot was flying straight and level. Five reaction time and time estimate samples were collected for each run of each maneuver for a total of fifteen samples per condition.

RESULTS

Analysis of the data revealed superior performance with the display on all primary and secondary dependent measures.

* Formula for calculating absolute deviation

\[ \text{AD} = \frac{\sum_{i=1}^{N} |X_i - \text{MD}|}{N} \]
Qualitative Data. Qualitative performance data for the Ps=0 and level turn maneuver from a typical subject is presented in Figures 3 and 4, respectively. Outputs show error from convergence for the three test runs. The lower line represents achieved condition, while the upper line represents the combined intermediate tolerance limits for all parameters. Results clearly indicate quicker and more consistently maintained convergence for display conditions than for the conventional instrumentation conditions. In addition performance in display conditions tended to be less affected by loading from the secondary tasks than the conventional instrument conditions, suggesting a general reduction in workload with the display.

Quantitative Data. Summarized data for time elapsed on condition for Ps=0 and level turn maneuvers is presented in Figures 5 and 6. For both maneuvers, subjects were able to spend a greater amount of time on the specified condition while using the display than when not using it. It should be noted however that facilitation of performance with the display was most dramatic for the more stringent tolerances. Performance in the Ps=0 maneuver showed no display related differences when error limits were broad.

In addition, an analysis of time spent on condition revealed task differences. The level turn emerged as the more difficult task, perhaps due to the additional requirement of achieving angle of attack. For the level turn, there was a slight facilitation of performance even for less stringent tolerances, although as for the Ps=0 the benefit of the display was greatest for the finest tolerances. Unlike for the Ps=0, the level turn revealed no display secondary task interaction. That is, secondary task loading affected performance as much when flying conventional instruments.

Data showing time to achieve condition is presented in Figures 7 and 8. Analysis of this measure also revealed superior performance when subjects were flying the display, particularly when tolerance limits were fine. The level turn was again revealed to be relatively more difficult than the Ps=0, and performance differences between display and conventional instrument conditions was less dependent on tolerance limits. With this measure different display/secondary task interaction patterns emerged between the two maneuvers when tolerances were fine. For the Ps=0, secondary task loading was more disruptive when pilots were flying conventional instruments, while for the level turn, the secondary task was relatively more disruptive in the display condition.

Secondary Measures. Reaction times were calculated from the onset of the cockpit light until the pilot depressed the trigger on the stick. Means calculated for the baseline condition and for each maneuver are presented in Figure 9. Baseline RT was .629, while test reaction times for Ps=0 were .859 and .607 for conventional instruments and display conditions respectively. For the level turn RT's were 1.21 and .894 for conventional instruments and display conditions respectively. Performance, as in the primary task, was superior in display conditions.

In addition task differences were revealed. The Ps=0 was again the easier task with RT's in the display condition actually falling below baseline levels. Although level turn reaction times were faster in the display condition than when flying conventional instruments, they were still considerably slower than baseline performance.

Two separate measures of time estimation were computed. One was the difference score between baseline and test condition estimates. For Ps=0 mean differences were +1.78 and -.11 for the conventional instruments and display conditions respectively. For the level turn difference scores were +2.57 and +1.07 for conventional instruments and display conditions respectively. Data is summarized in Figure 10. With this measure, performance is again clearly superior in the display conditions, for both maneuvers. Ps=0 estimates fell at baseline level with the display. Level turn estimates though less accurate overall than those made during the Ps=0, were improved when pilots flew the display.

Absolute deviations measuring the average dispersion about the mean were also calculated. The rationale behind use of this measure is that as primary tasks become increasingly difficult it is harder to attend to one's strategy producing accurate estimates. Thus, estimates become increasingly variable. Baseline variability was .651, while average deviations during the Ps=0 were 1.33 and .440 for conventional instruments and display conditions respectively, and during the level turn were 1.58 and 1.25 for the conventional and display conditions respectively (Figure 11). The data again show that performance is facilitated with the display, and supports the task related differences observed in previous measures.

DISCUSSION

The purpose of the current investigation was to evaluate the effectiveness of a newly developed display in aiding test pilots in flying difficult test flight maneuvers. All primary and secondary task measures indicated
that the display did indeed improve overall performance in the maneuvers flown. The results however deserve some further consideration with respect to extensions and provisions.

Tolerance Factors. While the data show a general improvement in flight performance with the display, this result is clearly most robust when tolerances are fine. This suggests that while the display is indeed effective, its practical application would most economically be limited to flight criteria which are stringent. This would include test flight conditions and fighter pilot maneuvers, and could presumably be extended to control of space station trajectory as well as control of peripheral vehicles and external manipulators.

Task Difficulty Factors. Another relevant finding was that of dramatic task differences in pilot workload. The Ps=0 consistently proved to be an easier maneuver than the level turn. A possible source of the relatively greater difficulty of the level turn was the presence of an additional parameter to monitor and control. While the Ps=0 required achieving and maintaining a specified Mach and altitude, the level turn also specified angle of attack. Data from individual parameters of the level turn demonstrated that angle of attack was indeed the most difficult to control. The data also indicated however that simplifying the perceptual signal with the guidance display was effective in improving flight performance.

This result has implications for the relationship between visual displays and manual control. Although manual control is often considered an independent dimension of pilot workload, a significant portion of manual control difficulty may be accounted for by the perceptual processing requirements of the task. In the present study the guidance display may eliminate the need to mentally transform sequentially derived visual feedback into appropriate control input by providing direct "fly to" information.

Secondary Tasks Factors. Both secondary task performance measures were consistent with the prediction of workload reduction with the display. Faster RT's to the cockpit light in display conditions can be interpreted as a result of a reduction in the perceptual scanning requirement, which thus freed perceptual processing capacity.

The display was also expected to reduce workload associated with the cognitive integration of a number of parameters required when flying conventional instruments. This integration which requires directed attention may be considered a form of "controlled processing" as suggested by the Schneider-Shiffrin model (Schneider and Shiffrin, 1977). Time estimation is a secondary task requiring sustained directed mental effort, and thus was considered to effectively tap residual attentional capacity (Hart, 1975). As predicted, time estimates made during maneuvers flown with the display were both closer to baseline estimates, and less variable than estimates made during maneuvers flown with conventional instruments. This suggests a better capacity to maintain a consistent estimating strategy during primary task activities when using the display. The display may thus free the pilot's attention to such an extent that peripheral information may be processed simultaneously. This may become significant in emergency situations where a peripheral warning signal must be apprehended or recovery procedures initiated.

As noted in the results section, the secondary task was found to be generally more disruptive to staying on condition when pilots were flying conventional instruments than when they were flying the display. This was the case however only for more stringent tolerances and only for the easier maneuver. Course error limits for the Ps=0 were most likely minimally taxing even in the conventional instrument conditions and thus performance was not significantly affected by the secondary task requirement. For the level turn however, workload was high in both the conventional instruments and display conditions. Maintaining the primary maneuver therefore may have occupied the pilot's attention to such a degree that the secondary task was periodically ignored or processed later. Support for this interpretation is provided by evidence for inferior secondary task performance during the level turn maneuver.

A somewhat different interaction pattern emerged for time to achieve condition. Here, the secondary task proved to be less disruptive in the display condition for the level turn. One possibility is that the workload associated with achieving the level turn using conventional instrumentation is so high that the secondary task received no attention for period of time. This would account for equivalent primary task performance with and without secondary task loading. The display however may have reduced workload to such an extent that the secondary task could receive some attention, and that attention allocation tended to degrade primary task performance.

These findings may bear on the general issue of parallel and serial information processing. During the performance of an easy task, parallel processing may be possible, that is, a single processing channel may have enough available capacity to perform two tasks simultaneously. As capacity becomes increasingly saturated however, the primary task suffers performance degradation. For difficult tasks
only serial processing may be possible. Under these conditions, channel capacity may be exceeded such that the operator must sequentially switch his attention from one task to another. Since each task is performed in isolation, with the primary task receiving the greater amount of time, no performance deficit occurs. Performance on the secondary task however does suffer.

CONCLUSIONS

In conclusion, some generalizations can be made about the characteristics of effective displays. First of all, a display should permit focal presentation of information. That is, the need to scan a wide range of instruments should be minimized. Secondly, a display should have task specific flexibility. Since every task is different, each will require that different information be available. A versatile display should possess simple signals which can signify the necessary information for a specific task. The use of advanced computer integration makes this possible and efficient. Thirdly, an effective display should supply relative status information. For many tasks it is not necessary that a pilot know the exact value of a particular parameter, but only his monetary distance from some prespecified goal. To the extent that a display can provide such general error information mental workload may be reduced. Finally, control input guidance information should be available to the pilot. Manual control workload appears to be significantly reduced if the transformation of current position information to appropriate control stick movements is carried out by computer interfration, and direct "fly to" information provided by flight instruments.

REFERENCES


Figure 1: Display Components

- Side indicator
- Vertical needle
- Roll axis scale
- Horizontal needle
- Throttle position scale
- Pitch axis scale
Figure 2: Conventional Instrumentation
Table 1: Test Conditions

<table>
<thead>
<tr>
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<td>h</td>
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<td>M</td>
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<td>$\alpha$</td>
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Table 2: Tolerances

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<tr>
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<th>&lt;$\alpha$</th>
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<td>1000' .1 2.5°</td>
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<td>1.5°</td>
<td>500' .03 1.5°</td>
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<td>.05°</td>
<td>100' .01 .05°</td>
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Table 3: Dependent Measures of Performance

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<th></th>
<th>h</th>
<th>M</th>
<th>$\alpha$</th>
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<tbody>
<tr>
<td>ERROR</td>
<td>&gt; 500°</td>
<td>.03</td>
<td>1.5</td>
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</table>

Qualitative

1) $h$
2) $\alpha$
3) M
4) $\sum h + \alpha + M$

Quantitative

1) Time elapsed on condition
2) Time to achieve condition

Secondary tasks

1) Reaction time
2) Time estimation deviation from baseline
3) Md time estimation
4) Ad time estimation
Figure 3: Qualitative performance from a single subject for $P_s = 0$ maneuver

$h = 20,000$°

Measure:
sum of absolute values of errors

Tolerance Scale:
$h = \pm 500$°
$M = \pm 0.03$

Conventional instruments baseline

Display baseline

Conventional instruments with secondary task

Display with secondary task

Time
**Figure 4:** Qualitative performance of a single subject for Level Turn

Measure:
sum of absolute values of errors

Tolerance Scale:
\[ h = \pm 500', \quad M = \pm 0.03, \quad \alpha = \pm 1.5^0 \]

<table>
<thead>
<tr>
<th>Measure</th>
<th>Conventional instruments baseline</th>
<th>Display baseline</th>
<th>Conventional instruments with secondary task</th>
<th>Display with secondary task</th>
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<td>Display baseline</td>
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<td>Conventional instruments with secondary task</td>
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<tr>
<td>Display with secondary task</td>
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</tbody>
</table>

Measure: sum of absolute values of errors

Tolerance Scale:
\[ h = \pm 500', \quad M = \pm 0.03, \quad \alpha = \pm 1.5^0 \]
Figure 5: Elapsed time on condition for $P_\alpha = 0$ maneuver (best 2 runs)

Time in Seconds
(higher scores indicate superior performance)

<table>
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<tr>
<td>Display</td>
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</tbody>
</table>

Scale:
- $h^+1000'$ $M^+0.1$
- $h^+500'$ $M^+0.03$
- $h^+100'$ $M^+0.01$

Figure 6: Elapsed time on condition for Level Turn maneuver (best 2 runs)

Time in Seconds
(higher scores indicate superior performance)

<table>
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<th>Secondary</th>
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<td>Instruments</td>
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<tr>
<td>Display</td>
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</tbody>
</table>

Scale:
- $h^+1000'$ $M^+0.1$ $\sigma^+2.5^o$
- $h^+500'$ $M^+0.03$ $\sigma^+1.5^o$
- $h^+100'$ $M^+0.01$ $\sigma^+0.0^o$
Figure 7: Time to achieve condition \( Ps = 0 \) (best 2 runs)

Figure 8: Time to achieve condition Level Turn (best 2 runs)

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<th>Instruments</th>
<th>Display</th>
</tr>
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<tbody>
<tr>
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</tr>
<tr>
<td>Intermediate</td>
<td>h(^+) 500' M(^+) .03</td>
<td></td>
</tr>
<tr>
<td>Fine</td>
<td>h(^+) 100' M(^+) .01</td>
<td></td>
</tr>
</tbody>
</table>

*Performance within course limits was within .07 seconds for all conditions.*
Figure 9: $\bar{X}$ Reaction Times for $P_s = 0$ and Level Turn maneuvers

Figure 10: $\bar{X}$ Time Estimates for $P_s = 0$ and Level Turn Maneuvers
Figure 11: AD (Dispersion around Median) for $Ps = 0$ and Level Turn Maneuvers

Deviation Scores (secs.)

$Ps = 0$

Level Turn