# NAVAL POSTGRADUATE SCHOOL

Monterey, California



# THESIS

A Comparison of Integrated
and
Conventional Cockpit Warning Systems

by

Joseph Dennis Mazza

September 1977

Thesis Advisor: D. E. Neil

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## REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER

2. GOVT ACCESSION NO.

3. RECIPIENT'S CATALOG NUMBER

4. TITLE (and Subtitle)

6 A Comparison of Integrated and Conventional Cockpit Warning Systems.

9 5. TYPE OF REPORT & PERIOD COVERED

Master's Thesis, 9/77

6. PERFORMING ORG. REPORT NUMBER

7. AUTHOR(s)

10 Joseph Dennis Mazza

8. CONTRACT OR GRANT NUMBER(s)

9. PERFORMING ORGANIZATION NAME AND ADDRESS

Naval Postgraduate School
Monterey, California 93940

10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS

11. CONTROLLING OFFICE NAME AND ADDRESS

Naval Postgraduate School
Monterey, California 93940

11 12. REPORT DATE

Sep[redacted]77

13. NUMBER OF PAGES

41 12 41 p.

14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)

15. SECURITY CLASS. (of this report)

Unclassified

15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Cockpit Design; Cockpit Displays; Cockpit Warning Systems; Master Monitor Display; Multi-Purpose Display.

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

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A Comparison of Integrated
and
Conventional Cockpit Warning Systems

by

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Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN OPERATIONS RESEARCH

from the

NAVAL POSTGRADUATE SCHOOL
September 1977

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# I. THE PROBLEM

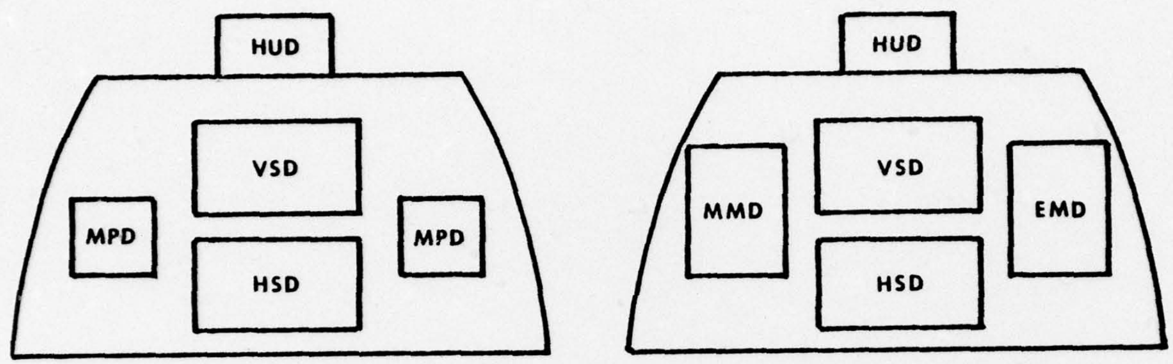
## A. BACKGROUND

Schultz [1968], in a study of information transfer in the modern jet cockpit, discussed the historical development of cockpit display systems. He found that early aviators relied almost entirely on direct observation for information concerning the performance of their aircraft. Airspeed was reckoned by the sound and feel of the slipstream; altitude by the size of objects on the ground; an engine's performance by its sound, vibrations, and appearance. As aircraft performance increased there was a corresponding increase in the amount and precision of information required by the pilot. Walters [1966] described the conventional instrument system which evolved to provide this information. The system consisted of a collection of discrete, dedicated instruments each of which sensed some physical quantity and displayed it in the cockpit for the pilot's use.

This system, with its refinements, has remained in use for many years during which aircraft have become increasingly complex and sophisticated. Bernberg and Gurman [1967] pointed out that the conventional system has two serious shortcomings: First, the area of the instrument panel is too small to contain dedicated instruments for all the information available in the complex, modern aircraft predicted for the 1980s. Second, even if some way were found to display all of this information, it would be too much for the pilot to assimilate.

Solution of these two problems was a point of major emphasis in subsequent cockpit display research from which the concept of an integrated cockpit emerged. Two examples of the development of this concept are the Digital Avionics Information System (DAIS) of the Air Force and the Navy's Advanced Integrated Modular Instrumentation System (AIMIS). Czuchry, et al. [1976] and Mulley [1975] discuss the conceptual designs for these two systems. They find that the trend in cockpit display design is to eliminate as many conventional instruments as possible and substitute a few large integrated displays to four ends: (1) To improve information transfer in the cockpit; (2) to standardize cockpit layout; (3) to integrate non-standard avionics into standard display formats; and (4) to reduce cost. Figure 1 shows panel layout proposals for these two systems.

These proposed systems contain the same classes of displays, in essentially the same positions. The heads-up display (HUD) and vertical situation display (VSD) have azimuth and elevation as a basic coordinate system and contain pitch, roll, heading, altitude, airspeed, steering and weapon release information. The horizontal situation display (HSD) is a plan-position indicator and presents geographic and navigation information such as heading, position, bearing, range, and cartography. Included on the panels is a new class of displays used to organize and




DAIS (USAF) AIMIS (NAVY)

Figure 1. Proposed Panel Layouts

present engine and fuel data, armament data, and system monitoring information. These are called variously, multi-purpose displays (MPDs), master monitor displays (MMDs), or engine management displays (EMDs).

## B. THE MASTER MONITOR DISPLAY CONCEPT

Lowe, et al. [1974] describes the MMD as follows.

> "The Master Monitor Display (MMD) is a data processing and display system conceived as an integrated component of an Advanced Integrated Modular Information System (AIMIS) and designed to provide an aircrew with an <u>integrated</u> presentation of warning and caution, functional status, mode advisory and auxiliary data on a single display surface. The MMD will serve as a replacement for the multitude of lights, indicators, and gauges which currently provide this status information to the crew."

Mulley [1975] similarly explains:

> "The increasing number of aircraft avionics systems are resulting in numerous readouts and monitoring panels in scattered locations of the cockpit. At present, most of these are incandescent bulb-light abbreviated identifications. A proposed caution-advisory panel of this type for a new aircraft (F-14) called for more than fifty abbreviated identifications. The possibilities of error both in readout and responsive action are increasing. A master monitor panel would spell out the problem and list alternate actions. This would unburden the pilot from monitoring numerous displays, [and] remembering the meaning of abbreviations and the required actions ...
>
> "The Master Monitor Display will also provide the pilot with warning and caution, mode advisory, functional failure, and auxiliary information, together with recommended action in critical situations, on a single display. This display will reduce the need for the individual warning and advisory lights that are now scattered throughout the cockpit."

Flat-panel matrix displays, because of their compactness, light weight and generally low power requirements, seem the most likely class of display to be used to implement the MMD concept. A typical proposal for such a display is shown in Figure 2.

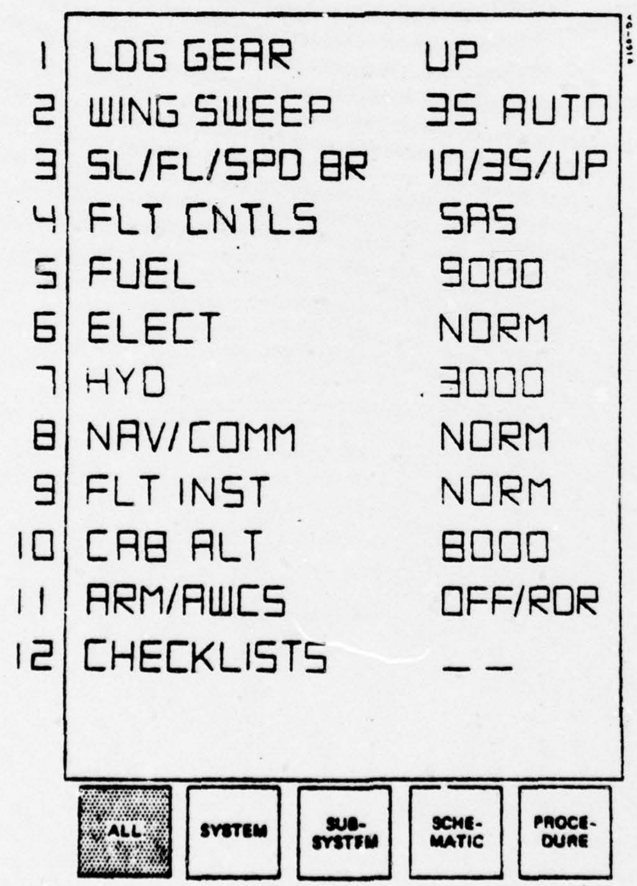



Figure 2. MMD Display from Lowe [1974].

Schultz [1968], in a discussion of some shortcomings of conventional warning systems states that in such systems the warning devices

> " ... are associated with, and usually located near, instruments which deal with the airframe and associated aircraft subsystems such as: fire, fuel, temperature and the like. A few warnings are associated with flight status, such as stall and overspeed. Some further confusion stems from the scattered location of such warning devices all over the cockpit, so that a pilot must in some cases 'work' to observe them."

Figure 3 presents a typical example of such an arrangement, taken from the cockpit of a P-3 aircraft.

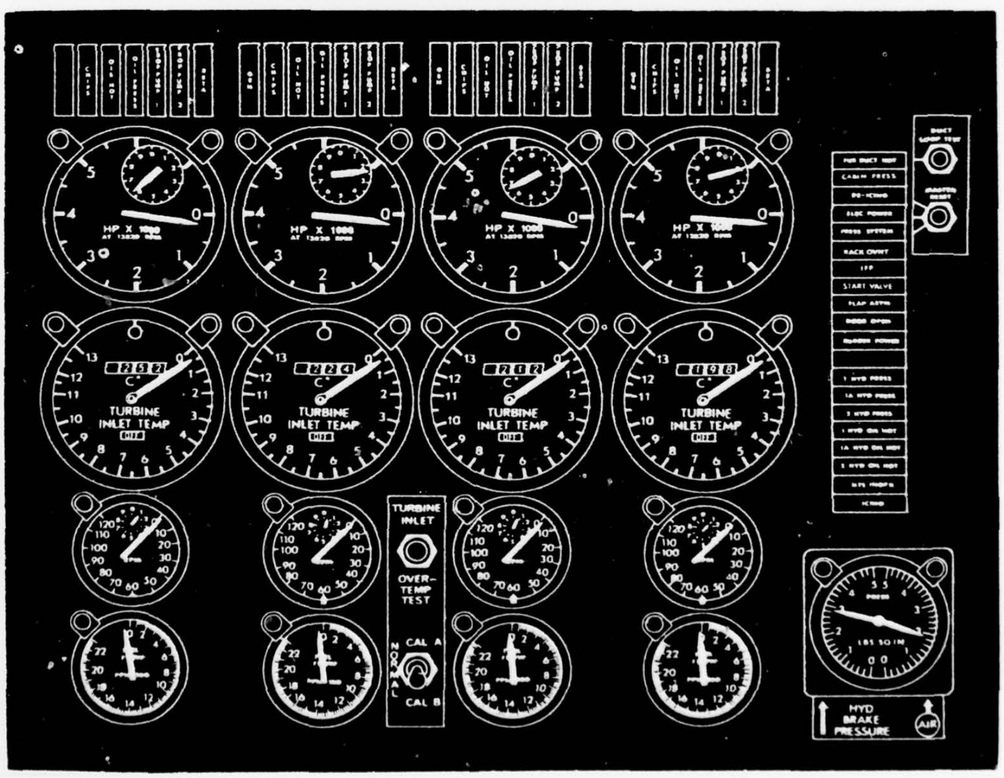



Figure 3. Instrument Panel Showing Warning Lights.

Unlike the MMD, which relies on alpha-numeric coding alone, this conventional design codes its information both alpha-numerically, through the labeling of lights, (shown above and to the right of the engine instruments in Fig. 3) and spatially by the particular location of each labeled light. Since each light is uniquely associated with a particular warning, all its information is carried in its spatial code alone. With enough training a pilot could actually interpret these warning signals even with their labels removed. Although they are neither taught nor expected to identify warnings by light position alone, pilots regularly receive information through this code. When a pilot sees one or more lights illuminated above the gauges for a particular engine he knows that a problem exists with that engine even before he decodes the specific warnings indicated by the light or lights.

A light's alpha-numeric label, while almost indispensable in interpreting the individual lights is, in a sense, redundant and in many cases carries insufficient information by itself to adequately describe the warning. Knowing that an "Oil Hot" light is illuminated provides insufficient information to allow the pilot to take corrective action. He must also know over which bank of instruments the light is located.

A symbolic display, of the type currently proposed for the MMD concept, relies on alpha-numeric coding alone. In a human performance evaluation of matrix displays Scanlan and Carel [1974] state that such symbolic displays

> " ... are those that present symbolic information in an abstract coded form. Because symbolic displays generally have only a single brightness level for the generation of symbols, the transmission of the code relies on shape differences. The code can be common, as in the case of alpha-numerics, or it may be a special set of symbols that have meaning only in a particular context. In either case the primary requirements are rapid and accurate discrimination of characters."

## C. PURPOSE

The question arises as to what effects this increased reliance on character identification and loss of spatial coding will have on the response time of subjects to a warning stimulus.

In a study of the variables influencing operator information processing Olson [1963] exposed subjects to various levels of rate of information presentation, the number of channels through which it was presented, and the physical location and arrangement of the display media. As Figure 4 shows, the mean transformed reaction time increased with the number of media channels used to present a constant amount of information. Olson concluded that on the basis of his results it would be reasonable to expect that a subject would be able to handle a greater inflow of information if it could be channeled through relatively few media. He predicted a slower response time with a greater number of media coupled with lessened performance on other required tasks.

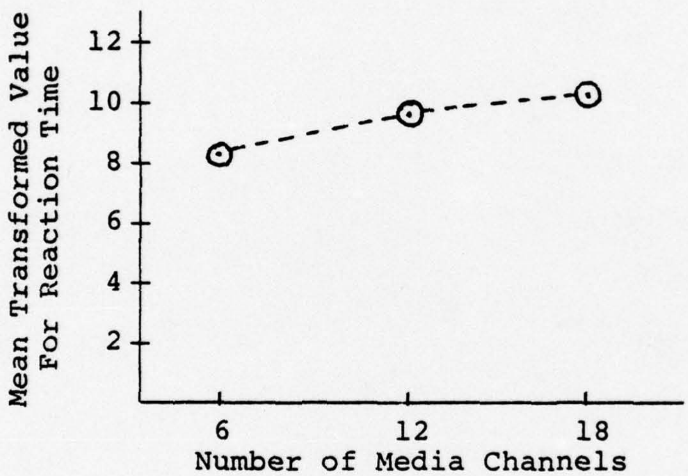



Figure 4. Results from Olson [1963].

While it is always dangerous to extrapolate beyond the data base, it might be reasonable to expect that a reduction of the number of media to one would result in continued improvement. If so, this would be an argument in favor of an MMD arrangement.

The present experiment was designed to test the hypothesis that the combined effects of the loss of spatial coding and reduction of media channels will result in no change (decrement) in the performance of subjects responding to an MMD type display as compared to their performance in response to a conventional type display.

In this experiment subjects responded to warning signals presented on displays simulating conventional and integrated systems. A secondary task was performed simultaneously to provide task loading.

# II. METHOD

## A. SUBJECTS

The subjects for the experiment were sixteen male military officer students and one male instructor from the Naval Postgraduate School. The sixteen officers ranged in age from twenty-six to thirty-three years, the instructor was forty-four years old. Subjects volunteered for the experiment.

## B. STIMULI AND APPARATUS

Subjects were seated at a table in a sound reduced booth facing a translucent projection screen onto which thirty-five millimeter slides were back-projected. In this technique, suggested by Schultz [1968], the slides used were black-and-white and presented warning signals in schemes representative of conventional or integrated designs. An example of a slide used to simulate a warning in a conventional system is shown in Figure 5. This slide indicated a fire in engine number three. The names and unique locations of the sixteen warning signals presented are shown in Figure 6. The warnings at the top were grouped by engine. Those for engine number one were at the left, for engine number two in the center, and for engine number three at the right. The lower matrix displayed miscellaneous warnings.

The engine warnings were placed in logical relative locations and groupings on the panel. This arrangement is

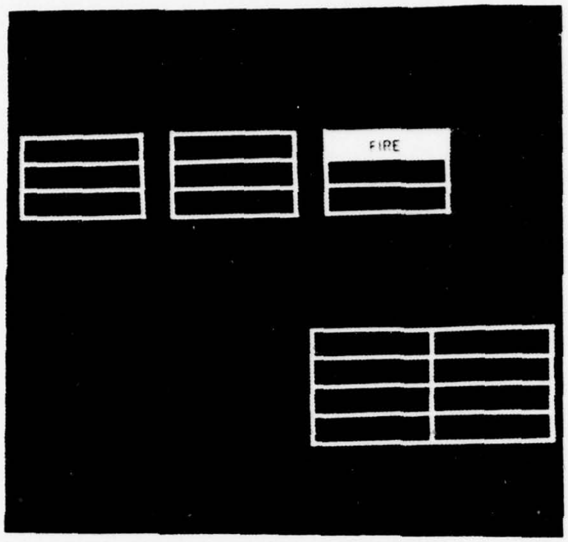



Figure 5. Example of a
Conventional Warning Display.

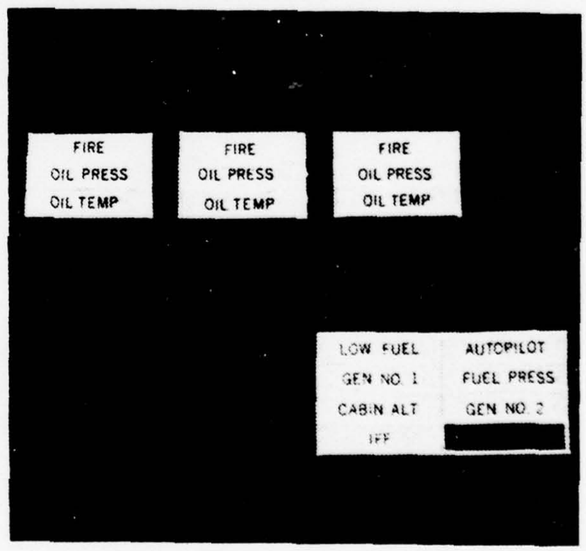



Figure 6. Warning Labels with
Positions on Conventional Display.

operationally defined to be well coded spatially. The miscellaneous warnings were intentionally placed at random with no logical order or grouping. This arrangement is operationally defined to be poorly coded spatially.

Two examples of the slides used to simulate an integrated system are presented in Figure 7. In these slides the position of a particular warning was not unique since all warnings appeared in the same place on the screen. The resulting ambiguity in certain labels was resolved by extending the labels as shown in Table I.

TABLE I

Extended Labels Used with the Integrated System

| CONVENTIONAL LABEL | INTEGRATED EQUIVALENT |
|---|---|
| FIRE | ENG FIRE NO. 1<br>ENG FIRE NO. 2<br>ENG FIRE NO. 3 |
| OIL PRESS | OIL PRESS NO. 1<br>OIL PRESS NO. 2<br>OIL PRESS NO. 3 |
| OIL TEMP | OIL TEMP NO. 1<br>OIL TEMP NO. 2<br>OIL TEMP NO. 3 |

NOTE: All other labels were the same in both systems.

A panel of push buttons was situated on the table in front of the subject and slightly to his right. Sixteen buttons were arranged in a 4 x 4 matrix and each was labeled to correspond to one of the sixteen warning signals as shown in Figure 9.

The nine buttons in the upper left portion of the panel were labeled to correspond spatially to the engine

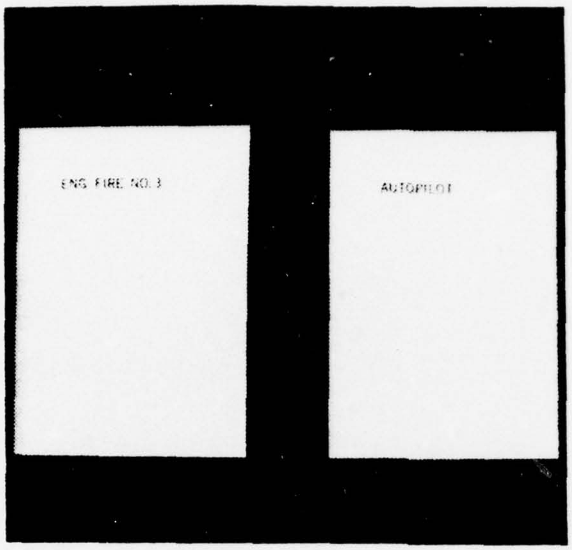



Figure 7. Two Examples of Integrated Warnings.

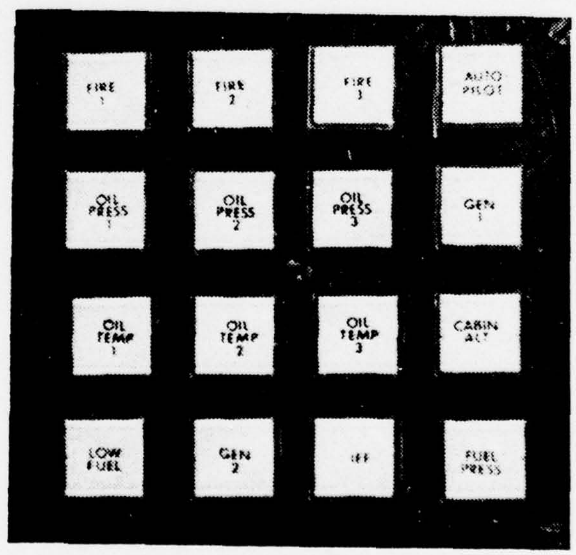



Figure 8. Push Button Panel.

warnings in the conventional display. The remaining labels were assigned at random.

A Texas Instruments TI-59 calculator mounted on a PC-100A printer was located on the table to the left of the button panel. In order to prevent inadvertent activation of erroneous keys and to reduce distraction, the calculator was covered so that only the numeric, decimal, change sign (+/-), and run/stop (R/S) keys were exposed and the printer was covered to conceal its output. A loudspeaker was placed in the booth and used to present the subject with taped instructions and aural clicks to be used as part of his secondary task.

C. PROCEDURE

Each subject was seated in the booth and given taped instructions for his first task, which was to respond to warnings presented on the screen in front of him. (Instructions to the subjects are contained in Appendix A.) He was told that when a warning appeared he was to press the labeled button corresponding to that warning as quickly and as accurately as he could. The timing was started when the projector shutter opened and stopped when the subject pressed a button. He was shown examples of warnings in the conventional system and given a practice session in that system during which sixty-four slides were presented at four second intervals with each warning repeated four times at random.

Due to external constraints placed on the length of the experiment it was decided to give no formal practice session using the integrated display. To compensate for this omission, when a subject first saw the integrated display (during a scored run) the first slide presented was counted as a practice/familiarization trial and the reaction time for that slide was not used in subsequent analysis. This decision seemed reasonable since the same push buttons were used with both displays and because the integrated presentation was simple and straightforward and, once seen, was easily interpreted.

The subject was then given instructions for his second task to be performed simultaneously with the first. He was told that his task was to count and record on the calculator the number of clicks presented at intervals over the loudspeaker. He was told to record the clicks by pressing the key corresponding to the number of clicks, then pressing the R/S key. He was told to use his left hand for the aural task and his right hand for the visual task. The aural stimuli were present in groups of four, five, six, or seven clicks in a manner similar to that used by Garvey and Knowles [1954]. The subject was given a short practice session during which he responded to four groups of clicks.

After the two practice sessions the subject was told that he would then begin a scored run during which he would perform both tasks simultaneously. He was instructed to do as well as he could on both tasks. The group to which the subject was assigned determined whether he received the conventional or integrated system first. In either case during the scored runs the time between slide presentations was equally likely to be any integer number of seconds from eight to sixteen. Each of the sixteen warnings was replicated four times at random for a total of sixty-four presentations per run.

During the scored runs the groups of aural clicks were presented at about seven second intervals. Ninty-nine groups were presented during each run. Each subject was exposed to the same sequence and timing of slides and clicks.

The second scored run for each subject was identical to the first except that the type of system simulated was changed to integrated or conventional as appropriate.

At the completion of the subject's second run he was asked to fill out a personal data questionnaire and requested not to discuss the experiment with other subjects.

## D. DESIGN

Data from the experiment were analyzed according to a three-way factorial analysis of variance (ANOVA) [Winer, 1962]. The three main factors were order of presentation (2 levels), display types (2 levels), and light groups (2 levels). Figure 9 is a conceptual model of the experiment.

The dependent variable for the study was mean reaction time. The subjects were divided into two groups, one

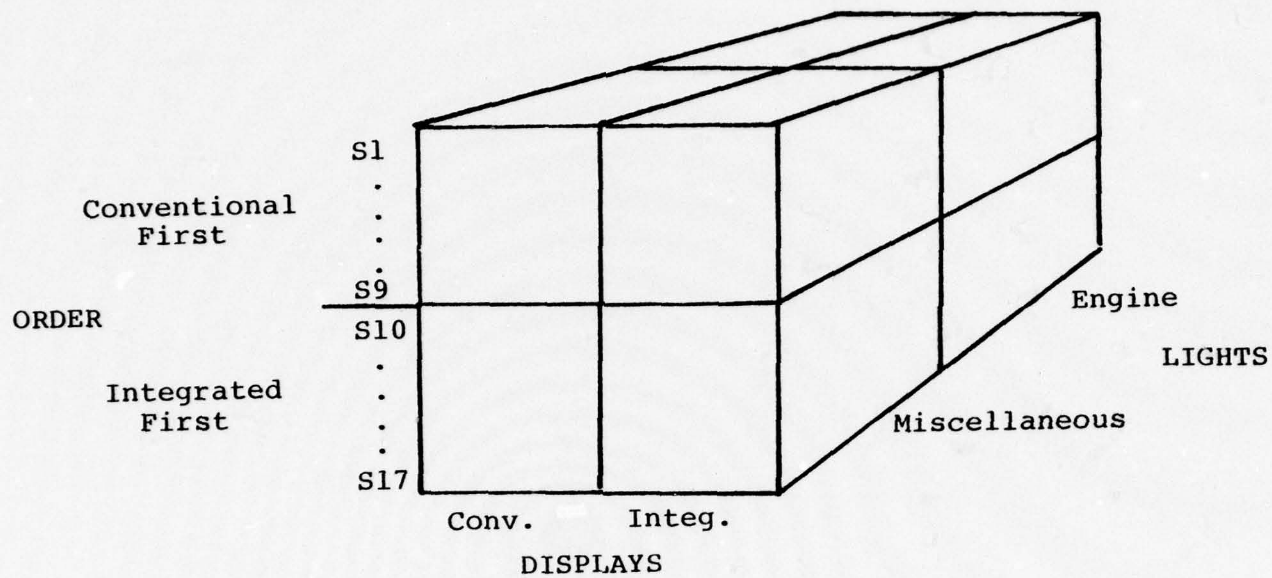



Figure 9. Conceptual Model of the Experiment.

receiving the conventional display first and one receiving the integrated first.

## III. RESULTS

Table II is a summary of the results of the experiment.

TABLE II

Mean Response Times by Subjects
Lights, and Runs

| | ENGINE LIGHTS | | MISCELLANEOUS LIGHTS | |
|---|---|---|---|---|
| SUBJECT | CONVENTIONAL (First) | INTEGRATED (Second) | CONVENTIONAL (First) | INTEGRATED (Second) |
| 1 | 1.27 | 1.77 | 1.98 | 1.92 |
| 2 | 1.07 | 1.27 | 1.33 | 1.37 |
| 3 | 1.42 | 1.72 | 1.82 | 1.96 |
| 4 | 1.00 | 1.26 | 1.37 | 1.37 |
| 5 | 1.25 | 1.42 | 1.54 | 1.54 |
| 6 | 1.32 | 1.76 | 1.48 | 1.83 |
| 7 | 1.69 | 1.82 | 2.03 | 1.90 |
| 8 | 1.24 | 1.56 | 1.66 | 1.89 |
| 9 | 1.29 | 1.94 | 1.75 | 2.01 |
| Mean | 1.28 | 1.61 | 1.66 | 1.75 |
| S.D. | 0.20 | 0.25 | 0.25 | 0.26 |
| SUBJECT | CONVENTIONAL (Second) | INTEGRATED (First) | CONVENTIONAL (Second) | INTEGRATED (First) |
| 10 | 1.08 | 1.84 | 1.46 | 2.49 |
| 11 | 1.26 | 1.92 | 1.54 | 2.26 |
| 12 | 1.28 | 1.95 | 1.45 | 2.26 |
| 13 | 1.40 | 1.97 | 1.73 | 2.24 |
| 14 | 1.07 | 1.58 | 1.17 | 1.68 |
| 15 | 1.34 | 1.96 | 1.66 | 2.19 |
| 16 | 1.37 | 2.13 | 1.54 | 2.32 |
| 17 | 1.65 | 2.39 | 1.98 | 2.56 |
| Mean | 1.31 | 1.97 | 1.57 | 2.25 |
| S.D. | 0.19 | 0.23 | 0.24 | 0.26 |

These results can be seen graphically in Figures 10 and 11. An analysis of variance (ANOVA) (Table III) indicated that there was a strong difference between displays and between light groups with a high degree of interaction between displays and light groups, between displays and order of presentation, and a significant interaction among light groups, displays, and order of presentation.

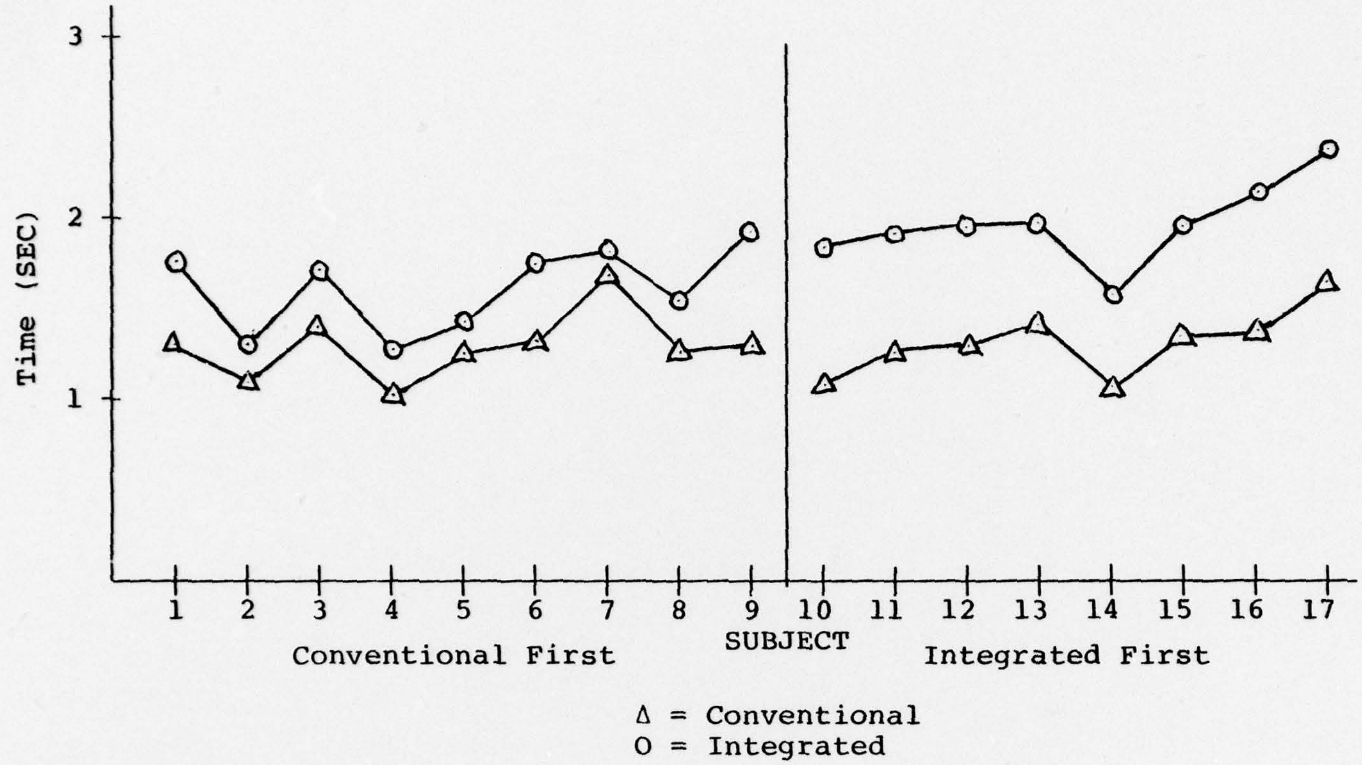



Figure 10. Mean Response Time for Engine Lights.

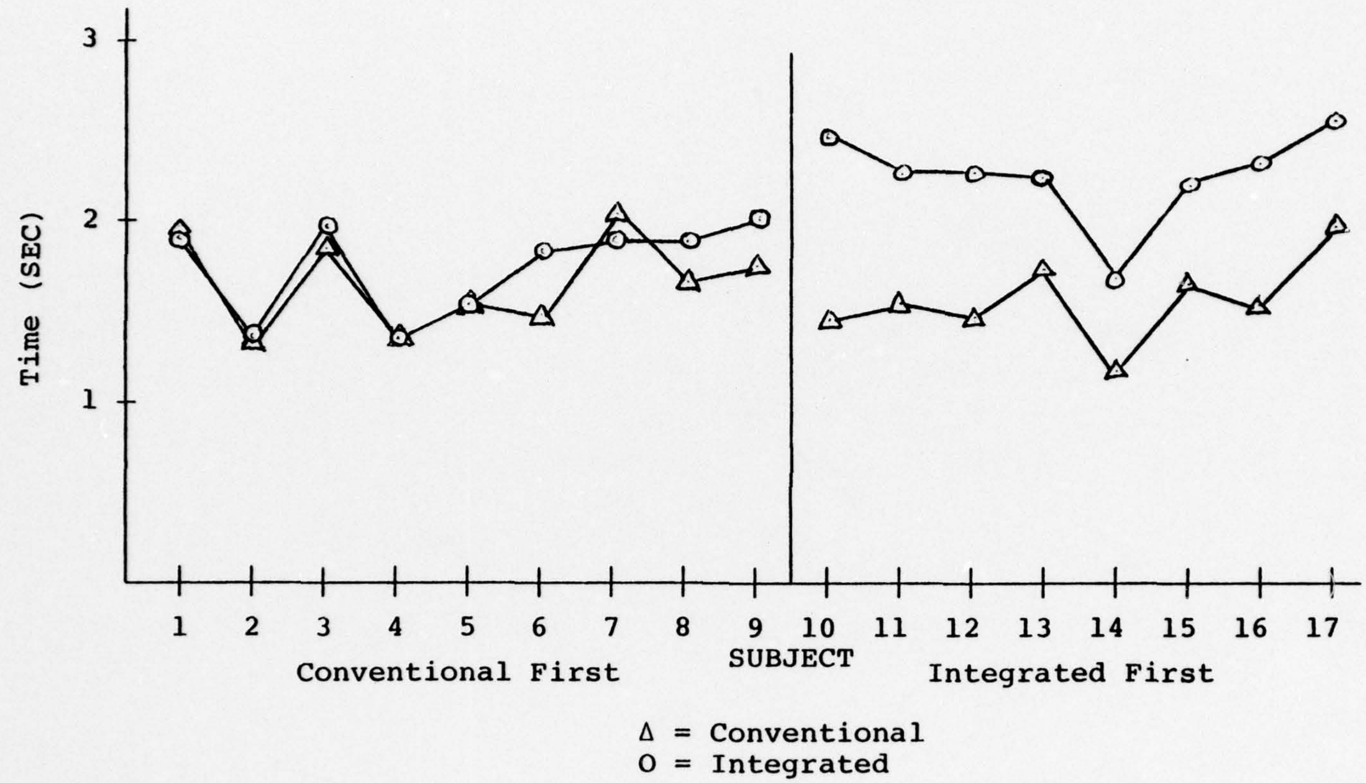



Figure 11. Mean Response Time for Miscellaneous Lights.

TABLE III

Analysis of Variance for the Experiment

| SOURCE | d.f. | S.S. | M.S. | F | P |
|---|---|---|---|---|---|
| Between Subjects | | | | | |
| Order (O) | 1 | 0.64 | 0.64 | 3.44 | 0.083 |
| Error | 15 | 2.78 | 0.19 | | |
| Within Subjects | | | | | |
| Lights (L) | 1 | 1.20 | 1.20 | 99.64 | 0.000* |
| L x O | 1 | 0.00 | 0.00 | 0.04 | 0.835 |
| Error | 15 | 0.18 | 0.01 | | |
| Displays (D) | 1 | 3.31 | 3.31 | 170.81 | 0.000* |
| D x O | 1 | 0.90 | 0.90 | 46.57 | 0.000* |
| Error | 15 | 0.29 | 0.02 | | |
| L x D | 1 | 0.05 | 0.05 | 9.26 | 0.008* |
| L x D x O | 1 | 0.07 | 0.07 | 13.53 | 0.002* |
| Error | 15 | 0.08 | 0.01 | | |
| TOTAL | 67 | 9.50 | | | |

* Significant at $\alpha = 0.01$

NOTE: Values are rounded to two decimal places for tabulation.

## IV. DISCUSSION

When considering the difference between displays it is convenient to consider the engine warnings and the miscellaneous warning separately.

In the case of the engine warnings it can be seen in Figure 10 that the subjects responded faster to the conventional display than to the integrated one regardless of the order of presentation. This result stems from the fact that in the conventional system the positions of the engine warnings and their associated push buttons corresponded spatially. As a result the subject, after a few minutes of practice, could press the correct button without actually having to read the warning label. This importance of compatability of display and control with respect to relative spatial location is consistent with the findings of Garvey and Knowles [1954], Chapanis and Lockhead [1965], and Poock [1969]. This experimenter feels that this situation accurately simulates a pilot's response to warnings that are well known to him and well coded spatially in the cockpit. (It should be noted here that the distinction made between "engine" and "miscellaneous" warnings is one of degree of spatial coding. The words "engine" and "miscellaneous" are used only to distinguish those lights that were well coded from those that were poorly coded in the conventional display. The fact that the well coded warnings were associated with the engines has no significance per se.) With the integrated display the subject had to first read the display and then respond to it, thus slowing his response time as shown. Heimstra and Ellingstad [1972] in a discussion of control coding also noted this extra time requirement to read labels and cite it as one of the disadvantages of using alpha-numeric coding.

In the case of the miscellaneous warnings the conventional display also usually produced faster mean reaction times. However, an examination of Figure 11 reveals that when a subject received the integrated system second, his performance on the two displays was nearly equivalent. Only two of these nine subjects reacted to the conventional display significantly faster ($\alpha = 0.05$). This result seems to indicate that the subjects were still learning throughout the experiment and that, with continued practice, the integrated display might prove to be as effective as the conventional. While this might be true in an experimental sense, in an actual flight setting the appearance of a warning signal is a relatively rare occurrence. This experimenter feels that measurements taken early in the subject's learning period more accurately approximate his performance in an actual flight situation.

Learning curves for the seventeen subjects were plotted by light groups and displays. Examination of the curves revealed only a very slight learning phenomenon. These results may, however, have been obscured by the interaction between the primary and secondary tasks.

The ANOVA also revealed a significant difference in mean reaction times between the engine and miscellaneous warnings. Reference to Figures 10 and 11 shows that the engine lights were reacted to faster than the miscellaneous lights in all cases. This result seems at first to be inconsistent. One would expect that there would be a difference using the conventional display since the push buttons were deliberately labeled to enable the subject to respond to the engine warnings without having to read them. But one would not expect to see such a difference using an integrated display in which all the warnings had to first be read then reacted to. The observed difference might be explained by the fact that the spatial coding of the engine push buttons shortened the subject's search time in both cases by enabling him to recode the alpha-numeric information on the button panel into a more economic spatial code in a manner described by Welford [1968] in his chapter on economy of decision. It is noted, however, that the difference between the engine and miscellaneous warnings was, as expected, more pronounced with the conventional system.

The interaction between displays and order of presentation was also shown to be significant. The data indicate that the integrated display was more sensitive to the order of presentation than was the conventional. Mean response times with the conventional display differed very little from subjects who received that display first to those who received it second. However, those receiving the integrated display second reacted significantly faster than those who received it first. This interaction might be explained as follows. The practice run for all subjects was made using the conventional display. The control/display (C/D) correspondence for the engine lights was learned rapidly and the subject could quickly respond to these lights without having to read them. When his first scored run was also made with the conventional system this knowledge carried over into that run and the subject's overall response time was lowered. But while reacting almost automatically using the spatial C/D relationships he was also learning the button locations in an absolute sense. This knowledge of absolute button locations then carried over into the second scored run (on the integrated system) reducing his search time for that run. However, when the first scored run was made using the integrated system the absolute locations of the buttons was still uncertain and, since no spatial cues were given by the display, the subject lost the luxury of responding automatically while learning these locations. Instead, his reaction time was, in part, dependent on this knowledge and slowed accordingly. On his second scored run (with the conventional system) the spatial C/D relationships again quickly enabled him to respond automatically with reaction times comparable to those by subjects who had the conventional display first.

Another significant interaction was that between lights and displays. It can be accounted for by observing that the miscellaneous lights were effected less by different displays than were the engine lights.

The significant three-way interaction among lights, displays, and order of presentation is indicative of the fact that the performance on conventional and integrated displays was nearly equivalent for miscellaneous lights by subjects who received the conventional display first, while in all other cases the performance was significantly different.

An examination of the errors made while responding to these systems is also of interest. There were no errors of omission, every warning was responded to in the time available. Using the conventional system there were only five errors of commission and no subject made more than one. Using the integrated system, however, four subjects made one error, four made two errors, three made three errors, and one made five errors for a total of twenty-six (over five times the number made using the conventional system).

Performance on the secondary task seems to have been independent of both error rate and reaction time for the primary task and fairly consistent across displays and subjects. Eighty-three secondary task errors were made on runs with the conventional system and seventy-two with the integrated. Eight subjects' secondary performance was better with the integrated display and nine did better with the conventional.

It seems, from the results of this experiment, that the hypothesized decrease in reaction time due to media reduction observed by Olson [1963] either did not occur or was of less magnitude than the increase in reaction time due to the loss of spatial coding.

# V. CONCLUSIONS AND RECOMMENDATIONS

It is recognized that an integrated warning system offers many advantages over a conventional one and that such a system will inevitably be placed in the cockpits of future fighter and attack aircraft. Its versatility, light weight, and compactness make it an attractive choice in a setting in which these factors are often critical.

It should be noted, however, that such a system is not without its disadvantages. This experiment has shown that mean reaction time to warnings presented on the integrated display was slower than that to those presented on the conventional display. Whether or not this statistically significant difference is significant in an operational sense must be determined in light of other factors such as the criticality of the warning involved and its sensitivity to reaction delays.

Further, it was observed that the number of errors committed with the integrated display was much greater than with the conventional, an unhypothesized result which warrants further investigation.

The author believes that further studies of possible shortcomings of an integrated display should be undertaken before such a system is installed in larger aircraft in which panel space and weight requirements are not as critical and for which a conventional system remains a viable alternative.

## APPENDIX A

## TAPED INSTRUCTIONS TO SUBJECTS

During this experiment you will be asked to perform two simultaneous tasks. The first consists of responding to slides presented on the screen in front of you. When a slide appears, you should press the appropriate button on the panel in front of you as quickly and as accurately as possible. You will be scored on both speed and accuracy.

This is an example of one type of slide. It simulates a type of warning system used in some aircraft. The warnings for engine number one are located at the left; for engine number two, in the center; and for engine number three, at the right. The lower panel displays miscellaneous warnings.

Take a few minutes to study the pattern and become familiar with where the individual warnings are located, both on the slide and on the button panel. [Two minutes given for study.]

A short practice session will follow. Please respond to the slide by pressing the approrpriate button as quickly and as accurately as you can. [Practice session follows.]

Your simultaneous task will be to count and record the number of clicks in a series of clicks presented to you on this recorder. After each series of clicks, key the total number of clicks that you counted into the calculator located to your left. Do this by first keying in the total, then pressing the run/stop key in the lower left-hand corner of the keyboard. It is important that you respond to each series whether or not you are sure of your answer. If you are not sure, you may respond by simply pressing the run/stop key alone, without keying in an answer. It is important that you respond to every series and that you press the run/stop key only once per series. You may not change an answer once it has been keyed in. If you think the answer that you have keyed is wrong, press the run/stop key anyway and go on to the next series.

A short practice session will follow, please respond as directed. [Practice session on aural task follows.]

A scored run now follows, use your left hand to respond to the clicks and your right hand to press the warning push buttons. You should try to do as well as you can on both tasks.

[The following additional instructions were given for runs using the integrated system.]

On this run the slides you will see are different from the ones you saw on the practice run. Their meaning will be obvious and you should respond to them the same way you did to the others.

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