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MEMORANDUM REPORT

U. S. AIR FORCE
AIR MATERIEL COMMAND
WRIGHT-PATTERSON AIR FORCE BASE
DAYTON, OHIO

TSEAA-694-1A

1 OCTOBER 1947

PSYCHOLOGICAL ASPECTS OF INSTRUMENT DISPLAY: I: ANALYSIS OF 270 "PILOT-ERROR" EXPERIENCES IN READING AND INTERPRETING AIRCRAFT INSTRUMENTS

PREPARED BY

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ENGINEERING DIVISION

U. S. AIR FORCES
HEADQUARTERS, AIR MATERIEL COMMAND
ENGINEERING DIVISION

TSEAA-8/PMF/jc

Date: 1 October 1947

SUBJECT: Psychological Aspects of Instrument Display. I: Analysis of 270 "Pilot-Error" Experiences in Reading and Interpreting Aircraft Instruments.

SECTION: Aero Medical Laboratory

SERIAL NO.: TSEAA-694-12A Expenditure Order No. 694-25

A. PURPOSE:

1. In order to determine methods of designing aircraft instruments so as to improve pilot efficiency and reduce the frequency of accidents, accounts of 270 errors made by pilots in reading and interpreting instruments have been collected and analyzed. Results of the analysis are presented in the present report.

B. FACTUAL DATA:

2. Accounts of errors were obtained through recorded interviews and written reports. The following question was used to elicit the desired information:

> "Describe in detail some error which you have made in reading or interpreting an aircraft instrument, detecting a signal, or understanding instructions; or describe such an error made by another individual whom you were watching at the time".

3. Pilots in the Air Materiel Command, the Air Training Command, and the AAF Institute of Technology, and former pilots in civilian universities contributed error accounts. Only detailed factual information furnished by an eye-witness or by the pilot who made the error was accepted. All reports were given anonymously.

4. It was found that all errors in reading or interpreting instruments could be classified into nine major categories. This classification is given in Exhibit A, pages 4, 5, 6, 7 and 8. Frequency of each type of error was as follows:

a. Errors in interpreting multi-revolution instrument indications accounted for 18% of the total error descriptions collected. The most common specific error was misreading the altimeter by 1000 feet. This 1000 foot error accounted for 13% of the total incidents collected.

b. Reversal errors accounted for 17%, signal interpretation errors for 14%, legibility errors for 14%, substitution errors for 13% and using inoperative instruments for 9% of the experiences collected.

c. The remaining 15% of error experiences were divided approximately equally among the following three categories; scale interpretation errors, errors

due to illusions and forgetting errors.

5. A description of the procedures used in the study, discussion and analysis of each type of error, and forty-two typical error descriptions are given in the Appendix.

C. CONCLUSIONS:

6. Instrument-reading errors are not confined to any single class or group of pilots or to individuals of any particular experience level.

7. The nature of instrument-reading errors is such that it should be possible to eliminate most of the errors by proper design of instruments. However, such redesign will not be possible until a great deal of research on human requirements in instrument display is completed.

8. On the basis of analysis of error experience collected in the present investigation, it is concluded that the most pressing psychological problems in instrument display are the following:

a. Discovery of more satisfactory methods of display for information, such as altitude data, that calls for the use of excessively long scales.

b. Tests of the hypothesis that one of the most important factors in insuring the proper interpretation of instrument displays is the use of a uniform direction-of-motion principle for all instruments.

c. Tests of the hypothesis that the cockpit reference principle is optimal from the viewpoint of pilot efficiency in interpreting instrument displays.

d. Development of improved warning devices and other means of conveying signals including methods of indicating that particular instruments are inoperative and methods of giving auditory signals.

e. Study of the variables influencing instrument legibility and determination of the degree of reading precision possible with different styles and sizes of dials, scales, pointers, and numerals.

f. Development of a practical system that will insure easy and positive identification of different instruments under night lighting conditions.

g. Study of scale design features favoring easy transition from one scale to another with minimum confusion between dials on which graduation marks signify different values.

9. The above list of research problems stems directly from consideration of the specific instrument interpretation errors made when using existing types of instruments. Another approach to better instrumentation is the development of new and novel methods of display which will permit major readjustment in the pilot's perceptual activities. As a basis for making such departures from convention, it is necessary that various possibilities such as pictorial displays, greater use of

auditory displays and methods of presenting on a single instrument more than one item of related information, such as a primary heading or position indication plus first and second derivatives of the primary value, or a single value in which several components are combined, be subjected to experimental study.

10. It is concluded that the list of problems outlined on the basis of the present investigation should form the basic framework for planning the long range psychological research program on cockpit instrument display problems.

D. RECOMMENDATIONS:

11. That the ten specific suggestions contained in the Appendix be reviewed by the Equipment, Aircraft, and Communication and Navigation Laboratories with reference to instruments for which each of these laboratories is responsible.

12. That the Aircraft, Equipment, Communication and Navigation, Aircraft Radiation and Armament Laboratories review the list of research problems outlined in the Appendix and comment on the relative value of answers to these various questions with respect to display problems for instruments now under development by the respective Laboratories.

13. That the report be reviewed by the Air Surgeon, The Assistant Chief of Air Staff for Training and Operations, and by the Flying Safety Division with respect to implications for pilot selection, pilot training, and flight safety respectively.

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EXHIBIT A

Classification of Errors Made by Pilots in Reading and Interpreting Aircraft Instruments

		No. of Errors	Percent Errors
1.	Errors in Interpreting Multi-Revolution Instrument Indications: Difficulty in synthesizing information presented by two or more pointers or by a pointer and a rotating dial viewed through a "window".		
	A. Errors involving an instrument which has more than one pointer.		
	1. Misreading the altimeter by 1,000 ft.	36	
	2. Other errors: Misreading the altimeter by 10,000 ft., the tachometer by 1,000 RPM, the clock by 1 hour.	4	
	B. Errors involving an instrument which has a pointer and a rotating dial viewed through a "window".		
	1. Misreading the tachometer by 1,000 RPM.	4	
	2. Misreading the air speed meter by 100 mph	4	
	Total.	48	18
2.	Reversal Errors: Reversing the interpretation of an instrument indication with the result that subsequent actions aggravate rather than correct an undesirable condition.	No. of Errors	Percent Errors
	A. Reversals in interpreting attitude information.		
	1. Reversals in interpreting the direction of bank shown by the flight indicator.	19	
	2. Reversals in interpreting the direction of pitch shown by the flight indicator.	3	
	B. Reversals in interpreting heading information.		
	1. Reversals in interpreting the gyro compass. . . .	12	
	2. Reversals in interpreting the remote compass and radio compass.	7	
	C. Reversal errors involving other instruments: (Trim tab indicator, oil pressure gage, oil temperature gage, landing gear indicator, altimeter).	6	
	Total.	47	17

		No. of Errors	Percent Errors
3.	Signal Interpretation Errors: Misunderstanding the message conveyed by hand signals or by warning horns or lights. Difficulties encountered in the interpretation of radio range signals.		
	A. Misinterpreting hand signals.		
	1. Interpreting hand and arm movements to reach a control as the signal to "retract landing gear"	6	
	2. Confusing one hand signal with another ("raise flaps" and "retract landing gear", "lock throttles" and "retract landing gear").	5	
	3. Failure to notice a hand signal.	2	
	B. Difficulties in interpreting radio range signals.		
	1. Confusing "A" and "N" when flying a range orientation problem.	6	
	2. Failure to perceive that the station identification signal is incorrect after having tuned to the wrong frequency.	4	
	C. Errors in interpreting warning signals - (failure to notice signal lights, confusing fuel warning light and marker beacon, confusing fuel warning light and heater warning light, failure to notice oxygen blinker not operating, confusing heater warning light and landing gear warning light, failure to notice warning horn)... .	6	
	D. Confusion regarding which pilot "has the controls" in aircraft with tandem seating arrangement	5	
	E. Misinterpreting signals from outside the aircraft (tower, formation leader, etc.).	3	
	Total.	37	14

		No. of Errors	Percent Errors
4.	Legibility Errors: Errors, usually of small value, which result from difficulty in seeing the numbers or scale on a dial distinctly enough to read the indication properly.		
	A. Instrument markings difficult or impossible to read because of improper lighting, dirt, grease, worn markings, vibration.	25	
	B. View obstructed: (inability to see an instrument because it is outside the normal field of vision, is hidden by something else in the cockpit, or because of frost on the inside of the glass covering the instrument	7	
	C. Parallax: (difficulty in reading an instrument as exactly as required because of the angle at which it is viewed; i.e., co-pilot flying from the right seat has difficulty in reading flight instruments which are placed on the left side of the instrument panel. . . .	5	
	Total.	37	14
5.	Substitution Errors: Mistaking one instrument for another, confusing which engine is referred to by a pointer of a dual indicating instrument, or failing to locate an instrument when needed.		
	A. Mistaking one instrument for another.		
	1. Confusing the manifold pressure gage and the tachometer.	19	
	2. Other: (confusing radio compass and remote compass, altimeter and rate of climb, fuel quantity and carburetor temperature gages, manifold pressure gage and altimeter, clock and air speed meter).	5	
	B. Confusing which engine is referred to by a pointer of a dual indicating instrument	6	
	C. Difficulty in locating an instrument because of an unfamiliar arrangement of instruments on the panel . . .	6	
	Total	36	13

		No. of Errors	Percent Errors
6.	Using an Instrument That is Inoperative: Accepting as valid the indication of an instrument which is inoperative or operating improperly.		
	A. Unknowingly using an inoperative flight indicator. . .	11	
	B. Unknowingly using an inoperative tachometer.	4	
	C. Unknowingly using other instruments which are inoperative - (gyro compass, needle and ball, remote indicating compass, oil pressure gage, landing gear position indicator).	10	
	Total.	25	9
7.	Scale Interpretation Errors: Errors which result from difficulty in interpolating between numbered graduations of scale or failure to interpret a numbered graduation correctly.		
	A. Errors in reading the scale between numbered calibrations (air speed meter, gyro compass).	6	
	B. Misinterpreting the meaning of calibration numbers (i.e., interpreting an "8" on the gyro compass as "8°" instead of "80°".	3	
	C. Unspecified difficulty in checking or interpreting the scale on an unfamiliar dial (air speed meter, flight indicator, gyrosyn compass, fuel gage).	6	
	Total.	15	6
8.	Errors Due to Illusions: Misconceptions of attitude which arise because of conflict between body sensations and instrument indications. Errors due to illusions which occur during the existence of instrument or marginal weather conditions.		
	Total.	14	5

		No. of Errors	Percent Errors
9.	Forgetting Errors: Failing to check or properly refer to an instrument before takeoff or during flight.		
	A. Forgetting to make a visual check of an instrument before takeoff or landing (suction gage, fuel gage, tachometer, voltmeter).	6	
	B. Forgetting to cross-check from one instrument to another during fligh (gyro compass and magnetic compass, flight indi tor, and needle and ball or air speed).	5	
	Total.	11	4

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Appendix I

TABLE OF CONTENTS

APPENDIX I

I. Introduction

The present investigation was conducted for the purpose of determining the kinds of errors made by pilots in reading and interpreting aircraft instruments. Underlying the study was the assumption that many s-called "pilot errors" are really due to the design characteristics of aircraft instruments. There is much data to indicate that this assumption is correct. It should be possible, therefore, to eliminate a large proportion of aircraft accidents by designing instruments in accordance with human requirements.

Not only should it be possible to prevent accidents by designing instruments that can be interpreted more accurately, but it should be possible to reduce the amount of time required for instrument readings and to increase greatly the efficiency with which pilots can carry out critical instrument flight procedures. Improvement in pilot efficiency and reduction in work load are essential for new high speed aircraft. However, before specific human requirements for improved instrument displays can be formulated or the research carried out to collect data needed by design engineers, it is desirable that the difficulties experienced in reading and interpreting current instruments be identified.

In the course of the present study, which was initiated late in 1945, accounts have been collected of 270 actual experiences of pilots in which errors were made in reading or interpreting aircraft instruments. Each account concerns a specific experience that happened to or was observed by the individual describing the event. These error experiences have been analyzed and classified into major types. Hypotheses have been formulated regarding how each type of error can be prevented through redesign of instrument displays.

The findings of a parallel analysis of errors made in using aircraft controls have been reported in Engineering Division Memorandum Report No. TSEAA-694-12. A subsequent report in this series will deal with general "peeves" of pilots regarding the cockpits and instruments in present aircraft and will be published as Engineering Division Memorandum Report No. TSEAA-694-12B.

The present report deals primarily with human requirements in the design of aircraft instruments. However, the results of the analysis of pilot errors can be applied also to the improvement of selection and training procedures.

II. Method Employed in Collection and Analysis of Data.

After different questions had been tried, a list of seven was selected for use in an interview. The present report is concerned only with the answers as the one of these questions which read as follows:

> "Describe in detail some error which you have made in reading or interpreting an aircraft instrument, detecting a signal, or understanding instructions; or describe such an error made by another individual whom you were watching at the time".

Fifty pilots were interviewed individually using all seven questions in the original list.[1] Each pilot was given the list to study a day or so before the interview. A permanent record of everything said during the interview was obtained by use of a magnetic wire recorder. These wire recordings were subsequently transcribed. Interviewers limited their comments to such interrogation as was necessary to elicit additional information when the accounts of experiences given in response to the questions were not sufficiently clear or detailed.

After completion of the individual interviews, fifty other pilots were interviewed in groups ranging from five to ten persons. The same questions were used as in the individual interviews. All individuals were given an opportunity to answer each question before the group proceeded to the next one. Several group meetings were held in order to cover all the questions.

Additional descriptions of errors in interpreting instruments were secured by the use of a printed form. This form contained a brief explanation of the purpose of the study and provided space for writing answers to three of the original questions, including the question on instrument interpretation. The printed forms were distributed to pilots in the Air Materiel Command, the Air Training Command and the AAF Institute of Technology and to former military and naval pilots attending civilian universities.[2]

A total of 524 printed forms were returned. Of these, only 187 contained descriptions of instrument interpretation errors. This was a substantially lower proportion of usable returns than was obtained in answer to the question on errors in using controls. This could be interpreted as indicating that pilots make fewer errors in reading instruments than they do in using controls. Or, it could be hypothesized that such errors often go unnoticed, or are harder to remember and describe.

In order to summarize and analyze the descriptions of instrument reading errors, it was necessary to develop clearly defined categories and to assign the descriptions of different errors to appropriate categories. The frequency of errors in each category was then determined and the different errors were analyzed from a psychological point of view with respect to the most likely underlying causes. Careful consideration also was given to the research investigations which

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1 Interviews were conducted by one of the following individuals: Dr. P. M. Fitts, Capt. R. E. Jones, Capt. G. Korinek, Lt. R. Showalter and Dr. W. B. Webb.

2 Replies from former pilots were obtained through the cooperation of the following individuals: Dr. C. W. Crannell, Miami Univ.; Dr. D. G. Ellson, Indiana Univ.; Dr. S. C. Ericksen, Vanderbilt Univ.; Dr. B. von H. Gilmer, Univ. of Virginia; Dr. N. Hobbs, Columbia Univ.; Dr. R. F. Jarrett, Univ. of California; Dr. J. G. Jenkins, Univ. of Maryland; Dr. W. E. Kappauf, Princeton Univ.; Dr. E. L. Kelly, Univ. of Michigan; Dr. R. B. Loucks, Univ. of Washington; Dr. A. W. Melton, Ohio State Univ.; and Dr. W. B. Schrader, Univ. of Tennessee.

are needed to provide the basis for recommending design changes to eliminate different types of errors.

III. Summary of Results

It was found that instrument reading errors can be classified satisfactorily into nine different categories. Each major category represents a different type of psychological difficulty. Within each major category errors are broken down into sub-categories, usually in terms of the particular instrument involved in the error. A brief definition of each type of error and the frequency with which each type occurred is given in Exhibit A, pages 4 to 8.

The two most common types of errors reported in the study were reversal errors in which the interpretation of an instrument such as the artificial horizon was reversed with the result that subsequent action aggravated rather than corrected an undesirable condition, and errors in interpreting multi-revolution instruments such as the altimeter.

Also occurring frequently were errors in interpreting signals such as hand signals or radio range signals, difficulties due to lack of satisfactory legibility of instruments, substitution errors in which a mistake was made in identifying an instrument, and instances of using an inoperative instrument.

The altimeter was misread more frequently than any other single instrument. By far the most common error in reading altitude was one of exactly 1000 feet. Experiences in which this particular error occurred were described by thirty-six different pilots.

The majority of the instrument interpretation errors collected in the present study were made by first pilots. As indicated in Table I, 125 individuals were acting as first pilot at the time of the error. Next most frequently described were errors made by Aviation Cadets. However, this category includes only 48 error descriptions. It can be concluded that the error categories developed on the basis of the present investigation apply to experienced pilots, and are not limited to errors made by student pilots.

TABLE I

Experience Level of Pilots at the Time Instrument Interpretation Errors Were Made.

	Number of Errors
First Pilot	125
Cadet	48
Rated pilot student	21
Copilot	32
Engineer	4
Not specified	40
	270

The majority of error descriptions concerned experiences that occurred during day flights. However, the number of errors reported as occurring during night flights is considerably higher than would be predicted from the fact that the majority of flying is done in the daytime. When exposure rate is considered, the results suggest that instrument reading errors are somewhat more likely to occur at night.

TABLE II

Relation of Time of Day to Frequency of Error Reports.

	Number of Errors
Day	140
Night	80
Not specified	50
	270

The majority of error experiences were reported for flights made under contact conditions. However, it can be seen in Table III that out of 214 reports in which the type of flight was specified, 79 error experiences occurred under actual or simulated instrument conditions. These data, when corrected for exposure rate, are interpreted to mean that errors are much more likely to occur under real or simulated instrument conditions than when pilots are flying contact.

TABLE III

Weather Conditions at the Time Errors Occurred.

	Number of Errors
Contact	135
Actual Instruments	52
Simulated Instruments	27
Not Specified	56
	270

A total of 34 different types of aircraft were involved in the 270 instrument interpretation errors. As will be seen from Table IV, the AT-6, C-45, B-26, B-24, and B-17 were the aircraft most commonly involved in instrument reading errors. The frequencies for different aircraft appear, therefore, to be roughly proportional to the amount of flying done in each type.

TABLE IV

Type of Aircraft in Which Errors Occurred

Type	No. of Errors	Type	No. of Errors
AT-6	47	P-51	5
C-47	34	AT-7	4
B-25	32	C-82	3
B-24	22	P-40	3
B-17	21	UC-78	2
B-26	12	AT-11	2
P-47	8	A-26	2
AT-10	8	PT-17	2
BT-13	8	B-34	2
C-45	8	13 other types	13
B-29	7	Not specified	20
P-38	5	Total	270

In the following sections, each type of error is considered in turn and examples are given of typical experiences in each category.

IV. Errors in interpreting the Altimeter and Other Multi-Revolution Instruments

Errors in instrument reading often occur when, in order to determine the exact numerical value of an indication, it is necessary to combine or synthesize data presented by two or more pointers on a single dial, or by a combination of a pointer and a set of digits viewed through a window in the dial. This category accounted for 18 percent of the errors reported. The characteristic of multi-revolution instruments which is the source of errors is that one revolution of a pointer on the standard-size aircraft dial (2 3/4 inches) cannot give a scale length sufficient to provide the needed reading precision. This has led to the use of multiple-pointer instruments, or the use of instruments combining a pointer and a window through which appears a numbered scale.

The altimeter is by far the most frequently misread instrument in this catagory. The conventional altimeter operates to approximately 40,000 feet with scale graduations every 20 feet. This means that the pilot must be able to distinguish a total of about 2,000 intervals. These 2,000 scale intervals are now indicated by means of three separate pointers on a single dial.

Typical descriptions of errors made by pilots in reading the altimeter and other multi-revolution instruments are given below.

Misreading the altimeter by 1,000 feet.

"It was an extremely dark night. My copilot was at the controls. I gave him instructions to take the ship, a B-25, into the traffic pattern and land. He began letting down from an altitude of 4,000 feet. At 1,000 feet above the ground, I expected him to level off. Instead, he kept right on letting down until I finally had to take over. His trouble was that he had misread the altimeter by 1,000 feet. This incident might seem extremely stupid, but it was not the first time that I have seen it happen. Pilots are pushing up plenty of daisies today because they read their altimeter wrong while letting down on dark nights."

"A pilot of my bomb group was making practice night landings in a B-29. The traffic pattern was to be 2,500 feet. The field elevation was 1,000 feet. The pilot misread the altimeter and was actually 1,000 feet lower on his traffic pattern than he thought he was. He went through his landing procedure, had his wheels down, flaps 30°, and was on his final approach. Before he realized what had happened, he flew into the ground about 1½ miles short of the runway. Luckily he hit in an open field, bounced, and managed to maintain flying speed. The main gear withstood the impact, but the nose wheel was ruined. By expert piloting, he made a safe landing and averted what could easily have been a disaster."

"In setting the altimeter of a B-17 to field elevation, I once made an error of 1,000 feet. Instead of setting the altimeter at plus 800, I set it at minus 200 feet. In this position, the large pointer also points to the 800 foot position."

Misreading the alimeter by 10,000 feet.

"I was flying at 25,000 feet in a P-47 on my first combat mission, but had mistakenly read the hands on my altimeter and was under the impression that I was at 35,000 feet. I called in some unidentified aircraft which were level with our formation and, consequently, actually at 25,000 feet. Since I mistakenly reported them at 35,000 feet, they were believed to be enemy aircraft. A good deal of confusion resulted. I believe some improvements can be made in our present altimeter."

Misreading the tachometer by 1,000 RPM.

"I was an instructor in a P-38 combat training group. One of my students had a generator go out. The procedure for this emergency was as follows: set props to 2600 RPM while control of same can still be maintained, turn off all electrical equipment and try to save some reserve battery strength for using radio in contacting the tower for landing instructions. 2600 RPM setting was considered sufficient if the ship were forced to go around after making the final approach. The tachometer on this particular ship was of the type where the indicator needle makes one complete revolution for each 1,000 RPM and the number of revolutions of the needle is indicated by numbers 1, 2 and 3 coming up behind a square cutout on the instrument. The pilot proceeded as instructed after loss of the generator and upon return approached the runway but was forced to go around with full throttle on both engines. He could not get sufficient power to regain airspeed and pick up his flaps and landing gear. The result was that he ditched in the water several hundred yards off the end of the runway. Later investigations of the pitch of the props indicated that they had been set for about 1,6000 RPM instead of 2,600."

Misreading air speed by 100 miles per hour.

"Our B-17 was in a fairly steep climb with some excess air speed following a dive. The pilot suddenly glanced at the airspeed indicator which appeared to read 90 MPH. The pilot instinctively pushed the nose down hard causing undue strain on the plane and crew. Actually the instrument was indicating 190 MPH. It was one of the newer type which is calibrated only up to 100 MPH on the outside scale and the hundreds are read through a window in the dial."

Analysis of Errors Made in Interpreting Multi-Revolution Instruments.

It will be seen from examination of Exhibit A that 1000 foot errors in reading the altimeter were described by 36 different pilots. Two cases of 10,000 foot errors were described, bringing the proportion of altimeter-reading errors to 14 percent of all those reported. In most instances, the pilot thought his altitude was greater than it actually was. The majority of errors were made in the air, although a number of reports described mistakes made on the ground in attempting to set the altimeter to field elevation.

It becomes obvious from analysis of the reports that mistakes in reading the 1000 foot or the 10,000 foot hand rather than the large 100 foot hand are to

blame for most errors. The exact nature of altimeter reading errors is being investigated in a special study conducted by Dr. W. F. Grether of the Aero Medical Laboratory. The portion of this study dealing with the relative frequency of errors and the different types of errors, and providing preliminary data on the interpretability of a number of alternative dial designs has been reported in Engineering Division Memorandum Report No. TSEAA-694-14. Further results will be presented in a later report, No. TSEAA-694-14A.

Other specific errors in reading multi-revolution instruments include misreading the tachometer by 1,000 RPM or the clock by 1 hour. These errors obviously are similar to the 1,000 foot altimeter error. The 10,000 foot error in altimeter reading is also similar, since it differs only in respect to the hand that is misread.

Errors in reading instruments which have a pointer and a rotating dial that is viewed through a "window" are similar in cause to those described above. As the pointer rotates clockwise from zero through 360 degrees and back to zero, the secondary dial which is viewed through the window moves slowly but continuously so that by the time the pointer has rotated about 300 degrees, much more of the numeral which will be reached when the pointer completes its rotation is visible through the window than of the numeral which actually indicates the number of completed rotations. As a result, the instrument sometimes is misread by an amount equal to one rotation of the pointer. Nearly always the error is to read the indication too high. Since this type of dial has been used on airspeed meters and tachometers, the common errors encountered are misreading the airspeed by 100 MPH (i.e., 90 is read as 190) and misreading the tachometer by 1,000 RPM (i.e., 1,850 RPM is read as 2,850 RPM).

Conclusions and Implications for Research.

This type of instrument-reading error is one of the most serious that can be made by a pilot since the magnitude of the error is large. The 1,000 foot altimeter-reading error is especially dangerous in view of the fact that the pilot usually believes himself to be higher than he is.

It can be concluded that instruments with either a combination of several pointers or a combination of one pointer and a numbered dial that is seen through a window, and that rotates in continuous rather than intermittent steps, are subject to misinterpretation when the pilot must read them hurriedly. High priority should be given to research necessary to find a satisfactory answer to this display problem.

Various possible ways of presenting exact quantitative information over a large range of values, and at the same time retaining those features which make it possible to check read an instrument at a glance, should be tried. Among the possible methods other than the two already in common use are the following: different dials and single pointers on each; a continuous tape viewed through a window; a tape combined with a veeder-type counter; a longarithmic scale; a scale with variable limits; a primary pointer showing gross values over the entire range of the instrument in combination with a secondary vernier scale to give more precise readings; and a dial having a single sensitive pointer combined with a vender-type

counter.

Another possibility would be the separation of check-reading from quantitative-reading. If this should prove successful, it would be possible to use veeder-counter type displays located in a secondary position for indicating exact numerical values and to employ greatly simplified dial-type instruments or all-or-none indicators for check reading. This separation of check reading from quantitative reading represents a radical departure from convention and is proposed only as a possible line for research.

V. Reversal Errors.

A reversal error in instrument reading is one in which an instrument indication is interpreted in such a way that any subsequent action taken to correct a deviation actually increases rather than decreases the undesirable condition. Nearly all the reversal errors collected in the present study were made in interpreting attitude and heading information from artificial horizon and directional gyro instruments. These errors resulted in changes in roll, pitch and turn which actually increased the amount of bank, degree of climb or dive, or deviation from desired heading. Other less frequent reversal errors included instances of reading in the wrong direction from a graduation mark and instances of using a reciprocal heading. A total of 17 percent of all reported errors were classified as reversals. The following are typical descriptions of such errors.

Reversal in Interpreting Direction of Bank.

"In the C-47, and similarly in all aircraft flown on instruments, I sometimes make an error in interpreting the flight indicator or artificial horizon. Very often when the miniature airplane indicates a degree of bank, in trying to correct the bank or level the wings, I have a tendency to increase the initial bank. This error is only momentary but it necessitates my spending too much time on the instrument, and failing to check other instruments often enough."

"I glanced away from the instruments while making a steep bank in a C-47. Upon glancing back at the artificial horizon, I was confused as to the direction of turn shown by the little pointer which indicates degree of bank. Upon beginning to roll out, I used exactly opposite aileron control from what I should and thereby increased the bank to such an extent that it was almost 90° and considerably dangerous."

Reversal in Interpreting Pitch.

"We were taking off in a B-24H from an airport in southern Florida at approximately 0500 hours under instrument conditions. The first pilot was relying primarily on the flight indicator for proper control of the ship's attitude after coming off the ground. The flight indicator showed that the ship was diving but the pilot misinterpreted it to read climbing. Control was put in which threw the ship into an even steeper diving angle, yet the

pilot still read the flight indicator as showing a climb. He realized the error only after an IAS of approximately 195 miles an hour was reached and the whistle of the slip stream on the cabin made the pilot realize that he had been misreading the instrument."

Reversal in Interpreting Heading From the Gyro Compass.

"I was flying instruments in a B-17 under the hood and had made several let downs. During one of these let downs, I was about to make a 'close-in procedure' and had my whole plan well in mind when I made a turn in the wrong direction. In other words, I read my directional gyro wrong."

"This incident happened while instructing in AT-10's. I had taken a student over to an auxiliary field to give him instrument takeoffs. About the third takeoff, (the others had been good) I lined up for takeoff, set the directional gyro, turned the airplane over to the student, and told him he was clear to go. As he started his takeoff run, the airplane began to go off to the left a little. He misinterpreted his directional gyro and gave it left rudder. He started out easy to try to bring it back, pushing a little bit on the rudder, then a little more and more. Then he got excited and gave it full left rudder. The ship cut off the runway across the grass, hit the taxi strip, bounced over the fence and into the air at a 45° angle to the normal takeoff direction."

Reversal in Interpreting Heading from the Radio Compass.

"We were making a navigation flight on instruments in a BC-1. Tail winds were 15 MPH more than predicted. The pilot turned on his radio compass to home on the Omaha Range when he thought he was about 5 minutes out. At the time he actually was past Omaha. The Omaha Range was not legible on the command set due to a sleet storm. The pilot misread his radio compass indicator and attempted to home with the station behind him. He eventually realized his mistake, made a 180° turn, homed, let down and ran out of fuel on the approach. Lucily, he made the field OK."

Reversal in Interpreting Trim Tab Scale.

"I pulled into position and started a normal takeoff in a Ventura patrol bomber. I gained momentum rapidly and soon had sufficient airspeed for takeoff. I eased back in the controls and they acted as if they were jammed. The end of the runway was coming close and I had about 100 knots airspeed. I pulled back as hard as possible on the controls and hauled the plane in the air by sheer strength. I rolled the elevator tab back to take the pressure off the controls. I found that I had set the tab 3° nose down instead of 3° nose up and that had caused all my trouble."

The Instrument Sensing Problem.

Since reversal of instrument sensing occurs so frequently, it will be worthwhile to consider in detail some of the causes of such errors. The general problem

is that of providing the correct sensing or meaning of the directions of movement of aircraft indicators and controls, in relation to the movements of the controlled object (the aircraft). This is an old problem which has elicited a great deal of discussion, but one which obviously has not been answered satisfactorily, and one about which there is still widespread disagreement among pilots and engineers.

Before going further, it will be necessary to define two terms, cockpit reference and external reference, which will be used frequently hereafter in the discussion of reversal errors.

A cockpit reference instrument is defined as one which, when the moving element (pointer or dial) moves up or to the right or clockwise with respect to the pilot's eyes, should be interpreted as indicating that the aircraft is moving up or to the right or clockwise with respect to the ground or a specified point in space. An external reference instrument is defined as one which, when the moving element (pointer or dial) moves up or to the right or clockwise with respect to the pilot's eyes, should be interpreted as indicating that the aircraft is moving down or to the left or counter-clockwise with respect to the ground or a specified point in space. The terms cockpit reference and external reference have been chosen because they are most nearly self-explanatory. Other common terms used by pilots and engineers when describing different principles for sensing the meaning of instrument displays are: 1) "fly to" versus "fly from"; 2) "existing deviation" versus "correction to be made"; and 3) "location or attitude of aircraft" versus "location of a point outside the aircraft." All of these terms are different ways of distinguishing between opposite poles of the same dichotomy. "Fly to", "correction that should be made", and "location of external reference point" are alternative ways of stating the external reference principle defined above. For example, the pilot direction indicator used on the bombing run could be called a "fly to" instrument since the pilot should turn in the direction shown by the needle. It also tells the pilot the "correction that should be made." The needle deviation also can be thought of as representing the location of the target since the needle points to the right when the target is to the right of course; i.e., if the aircraft is deviating to the left of course, the needle moves to the right. This instrument, therefore, also fits the definition of an external reference instrument.

It should be noted that the definitions of cockpit reference and external reference instruments are entirely operational and specify only the actual movement relationships between the pilot's eyes and the moving elements of the instruments. The question of how these movements are interpreted by the pilot is an entirely different matter - one that is the chief topic of the present discussion.

An inspection of any modern aircraft cockpit will show that contradictory direction of movement principles are now used in instrument design. The rate of climb and turn and bank indicators, for example, are cockpit reference instruments. The altimeter, airspeed indicator, tachometer, manifold pressure and all of the engine instruments also conform to the cockpit reference principle in that clockwise rotation with respect to the pilot always indicates an increase.

The conventional artificial horizon and the cross pointer (localizer-glide path indicator) on the other hand are external reference instruments, since their displacements with respect to the pilot's eyes are opposite to the direction of roll and pitch, and the displacement of the aircraft from the correct line of approach. 3 The radio compass and pilot direction indicator also are external reference instruments.

The new Sperry universal attitide gyro combines two opposing principles in a single instrument display. In this instrument, the roll indication follows the external reference principle, while pitch is indicated as on a cockpit reference instrument. For example, when the aircraft is in a climbing turn to the right, the instrument face is displaced upward but is rotated to the left in reference to the pilot's eyes.

The conventional magnetic compass and directional gyro are cockpit reference instruments in the sense that the drum carrying the heading graduations moves to the right, with reference to the pilot's eyes, when the aircraft turns to the right. This movement relationship is brought about by the fact that the pilot sees only the aft side of the stabilized drum. The drum is actually stabilized in relation to the magnetic poles of the earth (that is, in relation to an external reference point) but the side nearest the pilot has a motion the reverse of what would be the case if the pilot could see the front side of the instrument.

The newer remote indicating compasses usually are designed with circular dials in which degrees of heading increase in a clockwise direction around the dial. Some instruments have employed a fixed dial and a pointer that rotates clockwise in a right turn (cockpit reference in the upper half of the dial) and some have employed a fixed lubber line and a moving dial which rotates counter-clockwise in a right turn (external reference).

Analysis of Reversal Errors in Interpreting Attitude.

The proper directions of motion of flight instruments for maximum ease of sensing has been under discussion since instrument flying was inaugurated. In the report of the first flights in which hooded takeoffs and landings were made in 1929 by Lts. J. S. Doolittle and B. S. Kelsey (see reference 1), there is a discussion of the proper sensing of the Sperry artificial horizon and related flight instruments. However, after twenty years, the results of the present investigation indicate clearly that the problem has not been solved satisfactorily and that many mistakes in interpretation of flight instruments are still being made by AAF pilots.

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3 The cross pointer is an external reference instrument on the inbound course, but a cockpit instrument on the outbound course, since the sensing is reversed when the aircraft changes to a reciprocal heading.

The theory underlying the design of the conventional artificial horizon apparently has been that use of a moving horizon bar that is stabilized with respect to the real horizon will enable pilots to interpret the instrument without difficulty. Since the actual movement relations of cockpit and horizon bar duplicate the actual relations between cockpit and real horizon, many individuals have felt that the logic underlying this design is sound. Psychological research on space and movement perception has shown that it is dangerous to make such assumptions as this without experimental proof. Research on figure and ground relationships is particularly pertinent to this problem, for many difficulties in instrument interpretation that are otherwise not understandable are easily explained in terms of the concept of reversal of figure and ground relationships. A brief discussion of this concept follows.

Psychologically, an object is perceived as moving in relation to all of the other objects visible to the eye at the moment. For example, if an aircraft in flight is viewed from the ground, it will appear to move against the stationary sky. Similarly, a bright spot on a radar scope will appear to move in relation to the stationary sides of the scope. The part of the field of view that appears to be stationary in these examples is customarily called the background (or ground) and the moving object the figure. When all of the objects in the field of view move together in relation to the observer's eye, as is the case when the head is turned from side to side, the observer usually concludes that he himself is moving, and perceives the background as fixed or motionless. For any given configuration, there usually is a definite figure and ground and it is very difficult to reverse the relationship, i.e., to see the background moving and the figure motionless. In other words, it is very difficult to perceive a relationship in any way other than the natural one.

An hypothesis regarding the cause of reversals in interpreting the flight indicator has been postulated by Dr. W. F. Grether (see reference 8) in terms of the concepts of figure and ground outlined above. He states that, "The actual horizon is normally accepted by the pilot as a fixed or stable frame of reference against which his and other aircraft are moving figures. When the horizon disappears, as in instrument flying, the pilot apparently shifts to the cockpit of his own aircraft as the stable reference or ground against which all moving pointers, including the gyro horizon bar, are reacted to as figures. The small, narrow, fallible, moving bar in the cockpit apparently cannot substitute for the distant, massive and infallible true horizon as a stable frame of reference for the pilot. By reacting to the gyro horizon bar as a figure instead of ground, he is led to an exactly reversed interpretation."

Sometimes the movement relationships between two parts of the field of view are ambiguous. Such an ambiguous situation has been experienced by many passengers of railway trains. While looking out the window of a motionless car, they have seen a train on an adjoining track begin to move in relation to the window of their own car, and for a few seconds have experienced the sensation that they themselves were in motion. Similarly, a number of pilots have reported that when they first looked down from a spinning aircraft, the earth rather than the aircraft appeared to be rotating. These unusual experiences are mentioned by way of introduction to a discussion of the conflicts and ambiguities that now exist in the

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24

aileron correction. This percentage of reversals is low, but the important fact is that it should have been zero with pilots who had hundreds of hours of flying experience.

In summary, it can be concluded that the data gathered in the present investigation of pilot errors, the evidence from two carefully executed experimental studies with novices, and evidence from U. S. Navy experience in carrier landings all favor the cockpit reference principle.

Analysis of Reversal Errors in Interpreting Heading.

An inherent ambiguity in presenting heading information arised from the fact that in the actual flight situation, the pilot usually thinks of himself as if he were in the center of a compass rose with the points of the compass radiating across the earth's surface in all directions from himself. Aircraft compasses on the other hand conventionally present this information as if the pilot were looking at the earth (compass dial) from a position in space, i.e., from a point outside the familiar circle of the horizon.

The magnetic compass and directional gyro are ambiguous in another respect. They both utilize a moving drum instead of the more conventional moving pointer. Due to the fact that pilots see only the aft side of the drum, actual movement follows the cockpit reference principle, i.e., the drum appears to rotate to the right in a right turn. However, whenever graduation marks are thought of in reference to their actual meaning, relations are reversed. For example, if a pilot is flying contact on a course of North and using as a reference point a mountain which is directly on course, when he notices the mountain on his left he must correct to the left to regain the desired course; whereas, if he is flying instruments and notices that the "O" on the compass card is to the left of center he must correct by turning to the right. Thus, when Oo on the compass drum is to the pilot's left, actual North is to his right.

The change from a drum to a dial-type directional indicator does not solve all of the ambiguity inherent in heading indication. The rotating circular dial has a scale that increases in a clockwise direction and thus corresponds to the familiar compass rose, but during a turn, its movement is opposite to the direction of the turn. One airline has recently issued a report (see reference 2) proposing the use of a moving dial seen through a window at the bottom of the instrument face. This design thus preserves on a circular dial the type of scale and movements found in the conventional directional gyro.

A circular dial with movable pointer makes it possible to use a conventional compass rose, and for the pointer to move to the right during a right turn when the pointer is in the upper half of the dial. Between 90° and 270°, however, the right-left movement of the pointer is the reverse of that of the aircraft, unless the heading being flown is set at the top of the instrument.

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Analysis of Other Reversal Errors.

Reversal errors were reported, although much less frequently, for several instruments other than the directional gyro and gyro horizon. One characteristic is common to all these incidents. The direction of motion of the indicator is not that which is naturally associated with the condition or attitude that activates the indicator. For example, reversals are sometimes reported in reading the elevator trim-tab indicator on the C-47. On this indicator, degrees of trim nose down is read up from the center position while degrees of trim nose up is read down from the center position.

No specific errors were described in interpreting the localizer-glide path indicator. This may be due to the fact that the instrument is relatively new and has not been used by many pilots. Evidence from various sources suggests, however, that it is also subject to reversal errors when employed by inexperienced pilots who are at the same time using a full panel of flight instruments. In fact, the authors have observed such errors while conducting a project which required experienced pilots to make hooded approaches using this instrument.

Confusion of "A" and "N" signals when flying the radio range is a special form of reversal error. However, this error has been classified as a signal interpretation error in the present report and is discussed in a later section.

Need for Consistency in Design Principles.

Probably the most important single design factor contributing to reversal errors is the lack of uniformity in the principles employed in establishing direction of movement relationships for different instruments. The importance of this factor has been shown conclusively in recent experiments carried out by Mr. M. J. Warrick at the Aero Medical Laboratory. In several cases, it was found that either of two opposing principles are almost equally efficient when all control-indicator relationships are uniform, but that a great many errors are made when opposite principles are employed in associated instruments which must be used in rapid alternation.

The extent to which present instruments lack uniformity can be illustrated by the specific case of a pilot who is making an ILS approach and who begins to descend too rapidly and to deviate to the right of his proper course. His altimeter and rate of climb needles would show increased displacement in a counter clockwise direction, but his glide path needle would move upward and the horizon bar might also move upward. As a result of the deviation of the aircraft to the right, his rate of turn needle and directional gyro card would move to the right, while the degree of bank and localizer needles would move to the left.

The following reversal error in instrument interpretation, described by an instrument flight instructor, is another illustration of the confusion that may result from lack of uniformity in instrument sensing. His report follows:

"On frequent instrument flight checks, in the past 5 years, I have noted one particularly dangerous trait in pilots which is caused by inaccurate in-

strument interpretation. A pilot who relies on the artificial horizon as his primary reference when flying blind, tends to rely on the bank indicator of this instrument for indication of motion about the vertical axis. The bank indicator, on the artificial horizon, moves in just the opposite direction from the turn needle on the turn and bank indicator. When in a left bank, the turn needle on the turn and bank indicator is displaced to the left, while the degrees of bank indicator on the artificial horizon is displaced to the right. A pilot who utilizes the bank indicator on the artificial horizon for his primary reference as to motion about the vertical axis and amount of bank, may very easily become confused when the artificial horizon tumbles or is caged and he is forced to utilize the turn and bank indicator for his reference. In the past, I have had pilots make corrections in the wrong direction and in some instances have ridden out a split "S" which was a result of faulty instrument interpretation."

As a result of this lack of uniformity, the pilot must change his mental set each time he shifts his eyes from one instrument to another. He can undoubtedly learn to do this in time, as is shown by the skill attained by experienced instrument pilots. In fact, the shift in reference may in time become so automatic that experienced pilots are unaware that it is happening. But the necessity of constantly changing mental attitude certainly makes it more difficult to learn instrument flying and may lead to occasional reversal during emergency conditions. Numerous psychologists believe that under conditions of stress an individual is very likely to revert to earlier or more "natural" ways of reacting. If this is true, it would be especially difficult to shift from a natural to a learned mode of interpretation during emergencies.

Conclusions and Implications for Research.

The foregoing analysis of reversal errors should serve to clarify the direction-of-movement problem in instrument display. The results of the present investigation are in agreement with the findings from a number of research studies carried out by the Aero Medical Laboratory which show that present cockpit instruments are difficult to interpret and that serious reversal errors sometimes occur.

It is believed that tentative hypotheses can be formulated as to the best principle to follow in establishing direction-of-movement relationships for all instruments in the cockpit. However, additional research studies must be completed before optimum direction-of-movement principles can be fully established. The data now available lend support for two hypotheses which should be subjected to crucial experimental tests at the earliest possible moment. These hypotheses can be stated as follows:

Hypothesis 1. All instruments that must be cross-checked rapidly during critical maneuvers should be designed in accordance with a uniform direction of movement principle in order that no change in mental set be required in going from one instrument to another.

Hypothesis 2. The aircraft reference principle (in which the moving element of an indicator moves in the same direction, in relation to the pilot, as the aircraft is moving in relation to the ground should be followed in the design of instruments referred to in controlling the aircraft in situations where split-second reactions are demanded.

It is not unlikely that important exceptions will be found to these hypotheses even if they are proved to be generally correct. In some displays, the pilot may perceive and react to an indication as if the figure-ground relationships were different from what would be assumed without experimental tests. This might happen in some of the more ambiguous instruments such as those using a moving dial and fixed lubber line. The most important consideration, of course, is how the pilot interprets the indication, and not the actual movements occurring in the instrument. A further consideration is that instruments must be designed so that different individuals will make the same interpretation, and that a particular individual will make consistent interpretations.

The application of the two hypotheses should be investigated with special reference to combined indications. It is believed that combined instruments may justify special principles. For example, the instrument giving a combined indication of localizer and heading, being developed by the Communication and Navigation Laboratory, may justify the use of the external reference principle to represent the position of the localizer beam and the cockpit reference principle to show the heading of the aircraft.

Crucial tests of Hypothesis 1 should be made by means of simulated flying tasks set up in the laboratory and by actual flight tests involving the use of entire instrument panels designed in accordance with uniform direction-of-motion principles. This proposal points to the need for a new approach to flight instrument design research; i.e., the need for experimental evaluation of the total display in an aircraft cockpit.

It cannot be overemphasized that the pilot who must use his full set of instruments in critical maneuvers should have a panel in which he can shift from one instrument to another without conflict. Unless this can be accomplished, it is likely that training time to reach proficiency in instrument flight will continue to be unduly long, and that many improved equipments, such as new instrument landing systems, will be rejected because pilots find that a change in mental set is required each time a shift is made between the new display and other instruments.

Closely related to the problem of direction of movement of indicators is the interaction between instruments and controls. The final result of instrument comprehension is appropriate control action to achieve the desired change in flight path. Therefore, the problem becomes one of direction of movement of instruments, of controls, and of the controlled object. This problem, as well as the two hypotheses outlined above, is now being studied by the Aero Medical Laboratory, by other Laboratories, and by the University of Washington which has contracted to conduct research on orientation problems in aviation equipment design.

VI. Signal Interpretation Errors

Misunderstanding the message conveyed by hand signals or by warning horns or lights and errors in the interpretation of radio range signals accounted for 14 percent of the experiences collected. These signal interpretation errors have been classified into five sub-categories: 1) misinterpreting hand signals, 2) misinterpreting radio range signals, 3) misinterpreting or failing to notice warning lights, 4) confusion regarding which pilot has the controls (in aircraft with tandem seating arrangement) and 5) misinterpreting signals from outside the aircraft. Typical descriptions of signal interpretation errors are given below.

Interpreting a Hand Movement as the Signal to Retract Wheels.

"A new B-25 was brought to the field and assigned to our section. The pilot who was to take it up for a test flight had considerable time in B-25's but in the past 4 to 6 months had been flying B-26's. We got cut to the end of the runway behind a flight of B-17's and had to wait quite awhile. I remember the pilot saying something about the left oil temperature going up pretty high and shutting off the left engine until we were cleared onto the runway. Then he cranked it up again. The pilot poured on the coal to start down the runway, and just about the time the plane was about to be airborne, he reached up to the ceiling for the rudder trim, which is where it is located on a B-26. The copilot thought he was giving him the 'wheels up' signal. At about the same moment, the left engine coughed and the pilot reached out and cut both throttles. In the meantime, the copilot had raised the landing gear and we ended up on the far end of the runway on the belly of the plane. It was pretty well smashed up. There were four of us, the pilot, copilot, engineer, and myself, in the plane. Luckily we all got out safely."

Failure to Notice a Hand Signal.

"The signal was given to raise landing gear after takeoff in an AT-11. The copilot missed the signal. The pilot giving the signal was fighting prop wash and did not notice gear was not up until he was out of the traffic pattern."

Confusing "A" and "N" Radio Range Signals.

"I was on a non-stop ferrying flight from California to Wright Field at night in an A-26. This airplane carried no copilot, and I had no relief. Fatigue set in on the way from Tulsa to destination. On leaving Terre Haute, I tuned my radio to the Patterson Field range. I kept getting what I thought was an 'N' signal. I turned south looking for the 'A' zone, and did not 'wake-up' until over Cincinnati, where I realized that my ears were tired and I had been listening to the 'A' signal and interpreting it as an 'N'. Luckily, CAVU conditions prevailed and destination was reached without further incident. When watching a homing devic , without the constant buzzing in the ears, fatigue is not so extreme. I have never had difficulty on long ocean flights of the same duration as transcontinental, but when radio range signals have to be used continuously, the ears seem to fatigue after five or six hours."

Failing to Notice Wrong Station Identification Signal.

"The position of the command receiver in the C-47, overhead on the left side of the cockpit, resulted in the first pilot tuning in the wrong range. He was concentrating on the flight instruments and used volume as a means of tuning. Heedless of the identification signals the pilot tuned in the loudest station in the approximate frequency range of the desired station, bringing in a station located not more than 70 miles away. Orientation was tried with complete failure."

Confusing One Warning Light with Another.

"I was flying a C-47 as first pilot in the local traffic pattern with wheels down and checked. On the final approach the copilot lowered half flaps. Just prior to making contact with the runway, the copilot called for 'go-around' saying that the red landing gear warning light was on. When back at traffic altitude a check disclosed that while on the final approach the green landing gear warning light had come on. In this model aircraft, the heater spill valve warning lights and the red landing gear warning light are close enough together to cause confusion in a case of this sort."

Confusion as to Which Pilot Has the Controls.

"This experience happened in Advanced Flying School during a so-called 'buddy' or 'team' ride for the purpose of flying instruments under the hood. At the end of the flight while on the way back to the base, I was riding in the front seat and was performing some acrobatics when another AT-6 was sighted nearby. I made a signal pointing out the other plane. Just prior to sighting this plane, I turned the controls over to the pilot in the rear seat, or presumably so. The plane flew along for awhile straight and level and then began a slow lazy spiral to the left. The turn became more and more rapid and the aircraft finally went into a dive nearly straight down. The plane never did go into a spin. At an airspeed of 230, I began to wonder what the pilot in the rear was up to. Then I sighted a large trailer truck on a side road approaching the main highway ahead. The plane headed straight for the truck and was getting dangerously low. I unconsciously eased back on the control stick and the plane zoomed right over the top of the truck. In fact we were below the top of some telephone poles next to the road. The passengers of the truck unceremoniously departed from their vehicle. The plane zoomed to a height of 2000 feet, approached a stall, fell off to the left and once again headed for the ground. This time as the plane came close to the ground, I became scared and at the same time angered at the other pilot who would risk our lives in such a manner. So, I took the controls and flew back to the base and landed. When I had taxied up to the ramp and cut the engine, I proceeded to tell my buddy what I thought of his buzzing actions. He informed me that he thought I had done the buzzing. We helped each other to the barracks."

Misinterpreting Signals from the Tower.

"This student was on a night transition flight and had a defective radio. He was given a red and green blinking light by the tower. The student, without thinking or looking around, immediately pulled out on the runway and sat there. Another aircraft on the approach without lights did not heed the signal from the tower telling all aircraft to circle the field, but continued to land, hitting the cockpit of the ship on the runway with his prop and killing the pilot. We never found out what the pilot thought was the meaning of a red and green light."

Analysis of Signal Interpretation Errors.

There are three main types of difficulties encountered in interpreting hand signals. They are (1) failure to notice a signal, (2) interpreting hand and arm movement to reach a control as a signal, (3) and confusing one signal with another. There are several obvious explanations of failure to notice a signal; the man who should receive the signal may be inattentive; he may be so busy doing something else that he misses the signal; or the signal may be given in such a manner that the observer does not recognize it as a signal. Most of the errors in interpreting hand signals involve failure to identify correctly hand and arm movements made in reaching for controls during takeoff. The pilot may find it necessary to remove his hand from the throttles to adjust the trim for example and this may be interpreted by the copilot as the signal to retract landing-gear. Such an error is not difficult to understand when we consider that the pilot gives the "wheels-up" signal by raising his hand from the throttle with the thumb pointing upward.

Current AAF procedure is to employ only one hand signal (retract landing-gear). Apparently, there are pilots who because of former training, or because of personal preference, continue to employ hand signals to instruct the copilot to lock the throttles and raise the flaps. Both of these signals are sometimes confused with the signal to retract the landing-gear. They are both given during or immediately following the takeoff run. Both are made with the right hand. The "wheels-up" signal is given immediately after each takeoff while the others may be employed only occasionally. The copilot is expecting the signal to "retract landing-gear" and is set to make the proper control adjustment as soon as it is given. This mental set may explain why he retracts the landing gear when he is unexpectedly signaled to lock the throttle or to raise the flaps, Another possibility is that the pilot may make somewhat similar signals for the three operations.

Errors in interpreting warning lights are of two types. (1) failure to notice a warning light and (2) confusing one warning light with another. The location and appearance of the lights are probably the chief causative factors in these errors. The possibility of confusing adjacent lights is apparent, and is greatly increased of their colors are identical or similar.

Confusion regarding which pilot is flying the aircraft apparently occurs more often than might be expected in planes which have a tandem seating arrangement. The conventional signal utilized to inform another pilot that he should take over is to wiggle the stick. The same signal is used by the pilot who is not flying to inform the other pilot he is taking the controls. It is easy to see that in an aircraft which does not have satisfactory intercommunication these signals may be misunderstood and each pilot think the other is flying the airplane.

Misinterpreting signals which originate from the control tower, the formation leader, or some other outside source are occasionally reported. In such cases, it appears that the signal may not be sufficiently attention-getting for the pilot to notice it, the pilot may be expecting a different signal, or he may find it difficult to identify the signal.

Errors in interpreting radio range signals involve (1) failure to notice that the station identification signal is incorrect when the receiver is tuned to the wrong frequency, or (2) confusion between "A" and "N" signals. All student pilots are taught to use code at a much faster rate than is used on the range, and it is believed that inability to identify the coded signals cannot be blamed for the errors. Such errors are more likely to be due to inattention developing during long instrument flights or to changes in the perception of auditory temporal pattern after several hours of listening continuously to monotonous sounds.

The problem of reversal of radio range signals has been discussed in a recent report (reference 7) from the Harvard University Psycho-Accoustic Laboratory. In the introduction to this report, the authors state: "It is well to know that in some cases this effect is the result of abnormalities in the effective field strength patterns of stations radiating over mountainous terrain. Other reversals are caused by the well known "night effect". It can be shown further that reversals may occur when the output stages of receivers are overloaded and the signal is passed through conventional range filters. All three of these effects have been studied by conventional engineering methods. There remains the possibility of reversals occuring as a result of extreme pilot fatigue or other unfavorable listening conditions. To date all attempts to duplicate such reversals in the laboratory have met with only very limited success. Until a more convincing demonstration can be made that fatigue alone does produce reversals no report of these experiments is warranted." Evidence gathered in the present investigation would appear to furnish proof that fatigue or other psychological causes alone do produce reversals in the interpretation of range signals, since several of the experiences collected in the study are such as to rule out any other explanation.

Evidence for the possibility of improving radio range signals from the point of view of confusion on the part of the pilot is found in a study reported by R. C. Browne (see reference 5) in which he made comparisons of the American and British system of beam signals. He reports that a group of cadets that knew code but had no training in radio range flying made significantly fewer mistakes in identifying the American "A" and "N" signals than they did responding to British "E" and "T" signals. His report, for example, emphasizes that signals should differ in both tone and in pattern or rhythm, and shows that there is an optimal speed of signal transmission above or below which performance becomes worse.

Conclusions and Suggestions for Research.

It can be concluded that a great deal of improvement is possible in the design of both visual and auditory signaling methods. The principle avenues of improvement

are to increase the detectability or attention-getting value of signals and to increase the differentiability of various signals. The best signals are those that can be noticed and interpreted correctly with the least amount of training.

Suggestion 1. That the policy and training program with respect to the use of hand signals be examined with a view to complete or almost complete elimination of this method of communication and the substitution when necessary of mechanical signaling devices or spoken command.

Research on warning devices should be conducted for the purpose of determining the kinds of visual and auditory signals that are most attention getting, most readily identified, and that can be reacted to with least interference with other activities. The University of Maryland is now working on this problem under contract with the Air Materiel Command.

Research on auditory signals for use in instrument flight, such as in flying the conventional radio range is also warranted. The Psycho-Acoustic Laboratory has shown (see reference 7) that various auditory design variables, including signal intensity, signal-to-noise ratio, use of range filters, flat-response earphones and the radio range signal expander result in very significant improvement in performance by the listener. There is also evidence that the likelihood of confusing auditory signals can be greatly lessened.

VII. Legibility Errors.

Legibility errors are usually of small value and result from difficulty in seeing the numbers or scale markings of a dial distinctly enough to read the indication properly. These occur because of parallax, vibration, improper lighting, obstructed vision; because of faded, worn, or dirty dials and numerals; or because the numerals or markings are too small. In all, this type of error accounted for 14 percent of experiences collected in the present study. Typical examples of errors due to such causes are given below.

Instrument or Control Markings Difficult to See.

"Twice the pilot of our B-25 misread the manifold pressure gage on takeoff. He would advance throttles to 31" instead of 41" and attempt takeoff. I believe that this error was due to the fact that his instruments were old and the luminous numbers on the gages did not light up as bright as is desirable. I was riding as copilot and had to lean forward in the seat to read the gages and correct the pilot's error. The fluorescent lights were on bright at the time."

"A careful check was made utilizing the check list prior to starting the engines and again prior to takeoff in a C-46E1. All trim tabs were checked and seemed to be in proper alignment, although light in the cockpit was bad and the day was somewhat dark. The pilot made a hooded takeoff and during takeoff run, one wing came up as if it had been lifted by a cross wind. Opposite control put the aircraft on even keel. As soon as we became airborne, the left wing dropped with the airplane threatening to roll. The pilot, who weighed 190 lbs. and was

six feet tall, had to use full strength to hold the plane and assistance had to be obtained from the copilot until the cause was determined for this unusual occurrence. After checking the autopilot and engine operation, it was found that the aileron tab was rolled completely left wing down. The silver marks to indicate alignment were dirty and difficult to see."

View of Instrument Obstructed.

"In a flight from Austria to Italy in 1945, I was crossing the Alps at around 12,000 feet and the weather conditions caused me to go as high as 16,000 feet to avoid clous formations and severe electrical storms. Upon reaching Italy, I decided to go down rather quickly because weather conditions made it seem that the best thing to do was to descend rapidly. In this descent, I encountered a peculiar condition in that the whole instrument panel through precepitation fogged up, that is, moisture in back of instrument glass crystals all precipitated from the severe change in cold to warm moist air. If I had been on instrument conditions at the low altitude of Provalli, I would not have been able to read any of my flying instruments or engine instruments."

Error Due to Parallax.

"While leading a flight of four P-47 fighters on a combat mission, I.F.R. flight conditions were encountered. Upon entering clouds at about 1,000 feet, I experienced considerable difficulty in maintaining a straight heading and climbing up through the overcast. At about 1,300 feet, I went into a gradual spiral and lost altitude severely enough that the flight was lost and all four aircraft broke out at 1,000 ft. in various attitudes. I believe the reason for this experience was that in this particular ship the "turn bank indicator" was not in the direct sight line of the pilot."

Analysis of Legibility Errors.

Pilots report difficulties in reading instruments because of both insufficient and excessive cockpit lighting, but the former cause is much more common. In most cases involving insufficient lighting, it is either stated or implied that the difficulty occurs, not because the fluorescent lights fail to provide a light intensity that is sufficiently high, but because the light sources are so located that illumination is not uniform and it is impossible to light satisfactorily all the instruments at once. In attempting to adjust the level of illumination to a point where instruments on the perimeter of the panel are satisfactorily lighted the ultraviolet light sources must be turned so high that some instruments are too bright and there is reflection of visible light from surfaces in the cockpit.

Difficulties in reading the directional gyro constitute a special case. As the aircraft turns, the fluorescent marks on the compass card do not become activated fast enough to be read while the turn is in progress.

A few cases were reported of impairment of vision because the intensity of warning lights could not be adjusted to a sufficiently low level.

The trim tab indicator is the most common offender in instances of numerals being misread or not legible. In many cases, the numerals are printed directly on the control where they cannot be protected. With use, these numerals and graduation marks become dirty and greasy. The obvious result is an increase in reading time and in errors.

In some aircraft the relative position and size of the control column and the location of instruments on the panel is such that the pilot who varies from the average height has difficulty in seeing some of the instruments. Occasionally, accessory equipment is installed in such a position that the pilot's view of some instrument is blocked. Obviously, any obstruction between the pilot and the instrument he is using makes his job more difficult and increases the likelihood of errors.

Parallax errors, difficulties in reading an instrument as exactly as is required because of the angle at which it is viewed, were more often reported for flight instruments than for engine instruments. Most of these difficulties occur when the copilot is flying the aircraft and attempting to use flight instruments which are located on the pilot's side of the instrument panel. It is likely that experienced pilots can usually make satisfactory compensation for a considerable amount of parallax.

Difficulties in reading an instrument in which vibration of the instrument panel was given as the cause were reported infrequently. Probably pilots are accustomed to making compensations for considerable vibration and can do so satisfactorily. However, it is possible that smaller amounts of vibration may indirectly increase errors and bring on fatigue more rapidly.

Conclusions and Recommended Research.

Legibility is one of the essentials of a satisfactory display. The fact that only 14 percent of reported instrument-reading errors were classified in this category suggests that on the whole present instruments and cockpit markings are adequately discriminable. On the other hand, we are justified in concluding that considerable improvement is possible. Better legibility should bring with it other benefits, such as less time for both check reading and quantitative reading, and the possibility in some instances of using somewhat smaller instrument dials.

The following suggestions are made with regard to specific steps that can be taken to improve legibility.

Suggestion 2. Provide more uniform distribution of ultra-violet light over the instrument panel.

Suggestion 3. Provide some means for quicker activation of the markings on the directional gyro during a turn.

Suggestion 4. Provide adequate safeguards to insure that markings on all instruments and controls cannot become illegible from dirt, grease, wear and fading. Regular inspections should

be made of the fluorescing qualities of instrument dials and unsatisfactory dials replaced.

Suggestion 5. Design instruments so that it will be impossible for the inside of the glass covering the dial to frost.

There are a number of legibility problems which warrant extensive research. These can be listed briefly as follows:

1. Optimal shape, proportions, and stroke width for numerals and letters.

2. Minimum size of numerals and markings required for adequate legibility under conditions of vibration and low illumination.

3. Optimal design of instrument scales and pointers for maximum speed and accuracy of quantitative reading.

4. Optimal design of instrument scales and pointers for maximum speed and accuracy of check reading.

5. Optimal wave length, intensity, and contrast relationships for providing adequate night lighting of instruments, while at the same time mirimizing fatigue and maintaining dark adaptation.

Research on these problems is being conducted under contract with the Air Materiel Command by Princeton University, Tufts College, and the University of Rochester. Some work also is being done directly in the Aero Medical Laboratory.

VIII. Substitution Errors.

Pilots report making three kinds of substitution errors, (1) mistaking one instrument for another, (2) confusing which engine is referred to by a pointer on a dual indicating instrument and, (3) difficulty in locating an instrument because of the unfamiliar arrangement of instruments on the panel. This type of error accounted for 13 percent of those reported. Typical experiences are quoted below.

Confusing Tachometer and Manifold Pressure.

"I have mistaken the tachometers for the manifold pressure gages on night takeoffs in a C-47 because they are very similar in appearance under fluorescent lights. This has never resulted in an accident but produces a momentary confusion for the pilot during a critical period of operation."

"Having flown the P-40N model in RTU, I was quite accustomed to the placement of instruments on the panel of this particular model and could read and interpret them very quickly. Upon arrival overseas, I found we had the usual P-40N models and one K and one F model. It was on takeoff in the K model that this incident happened. The plane was equipped with an old type tachometer and the instrument was in the exact place which I normally expected the manifold pressure gage to be. The instrument read 30 at the top of the face which in

reality was 3000 RPM. I was under the assumption that I was reading 30 inches of mercury. As I pulled the RPM control back to climbing RPM, my eyes were on the tachometer. The needle dropped and I immediately advanced the throttle to correct for what I thought was manifold pressure drop. The engine began to run rough at this low RPM and extreme manifold pressure. I then checked all the gages and discovered the high reading on the manifold pressure gage and it dawned on me that I was making the mistake of reading manifold pressure from what was actually the tachometer."

Confusing Carburetor Air Temperature and Gas Gage.

"I was copilot one night in a C-47 and the pilot asked me how much fuel we had. I said half a tank on the particular tank we were using. Thirty minutes later, he asked me again and I thought it still read half a tank. I thought something was wrong with the gage. I asked the pilot if he had the fuel selector set right and he replied 'yes'. The reason for the error was that the carburetor air temperature was directly below the gas gage and the needle was pointing straight up and down. I had mistaken it for the gas gage."

Confusing Which Engine is Out on a Dual Indicating Instrument.

"During day transition, I was acting as instructor pilot. My student was given a simulated single engine. The needles of the manifold pressure gage (one instrument for both engines) were marked '1' and '2'. The needles on the RPM indicator (one instrument for both engines) were marked 'L' and 'R'. When the engine failed, the student performed the single engine sequence in the proper order until it was necessary to retard the dead engine throttle. He then retarded the live engine throttle and would have completed the procedure and feathered the good engine if I had not stopped him. The student stated that he became confused between 'L' and 'R' and '1' and '2'. The student was previously advised not to determine engine failure by use of manifold gages or RPM indicators alone.

Unfamiliar Arrangement of Panel Instruments.

"We had an alert one morning about eleven o'clock, because about 35 Japanese planes had been picked up on the radar screen. In the mad scramble for planes, the one I happened to pick out was a brand new ship which had arrived about two days previously. I climbed in and it seemed the whole cockpit was rearranged. Finally, I got it started but the Japs hit just about that time. The rest of the gang had gotten off and were climbing up to altitude. I took a look at that instrument panel and viewed the gages around me, sweat falling off my brow. The first bomb dropped just about a hundred yards from operations. I figured then and there I wasn't going to take it off but I sure could run it on the ground. That's exactly what I did - ran it all around the field, up and down the runway, during the attack."

Analysis of Substitution Errors.

The most common substitution error is confusing the manifold pressure gage

and the tachometer. Other instruments that were confused with each other are the radio compass and remote compass, the altimeter and rate of climb, the fuel quantity gage and carburetor temperature gage, the manifold pressure gage and altimeter, and the clock and airspeed meter. Among the causes of substitution errors are proximity of the two instruments, similarity of the dials, and lack of uniformity of location of the instruments on the panel. It is likely that in many cases two or even three of these factors may be operating in conjunction. It should be pointed out that in some aircraft, the throttles are on the right of the RPM control, whereas on the instrument panel the manifold pressure is on the left and the RPM gage is on the right. This possible cause of confusion should be eliminated. Nearly all substitution errors occurred at night. Under ultra-violet illumination, instruments tend to look alike because only major numerals and markings are visible.

Difficulty in locating an instrument because of the unfamiliar arrangement of instruments on the panel is a transition error, i.e., it is made by experienced pilots who are using an instrument panel in which certain familiar features are changed. The difficulty may be brought about because an instrument is in a different position from what is usual or because the instrument in question has a non-uniform type of dial which is so different from that to which the pilot is accustomed that he does not recognize it as quickly as is necessary.

Conclusions and Recommended Research.

It is concluded that there is a danger in making two or more instruments look too much alike. The trend toward standard sizes and simplified markings without uniform location of instruments has accentuated the probability of substitution errors, especially at night. Confusion regarding which engine is out in an especially serious error and considerable effort in designing engine instruments which will prevent this confusion is warranted.

The following suggestions are offered as means of reducing substitution errors.

Suggestion 6. Provide uniform pattern arrangement of instruments on the panel.

Suggestion 7. Replace dual indicating engine instruments with single indicating instruments.

Suggestion 8. Provide uniform and distinctive dials for instruments that can be confused, and especially for tachometer and manifold pressure instruments.

The benefit that would result from uniformity between the instrument panels of different aircraft is obvious. On the other hand, it is desirable to introduce new and improved instruments from time to time. It would appear, therefore, that the problem can be solved only partially through uniformity in instrument design and location.

The differentiation of different instruments and different engines requires research for its solution. One problem is the best method of providing distinctive identifying designs for different instrument dials. Another problem is the optimal pattern arrangement of engine instruments and pointer positions for most rapid check reading. Some of these problems are now under investigation at the Aero Medical Lab.

IX. Using An Instrument That Is Inoperative

Pilots report numerous cases of using flight indicators and tachometers that are inoperative or operating improperly. This error accounted for 9 percent of the reports gathered in the study. Unless an instrument has a warning device which shows when it is not operating properly, the pilot must determine this fact by cross-checking against other instruments. Even after cross-checking and observing a discrepancy between two instruments, in many cases the pilot cannot be positive which indication to accept as correct. Most flight indicators now in use have a flag to show when the instrument is caged, but no indication to show when it has tumbled. Examples of pilot experiences in using inoperative instruments are given below.

Using an Inoperative Flight Indicator.

"This experience occurred while I was flying a C-47 on a night supply dropping mission. My copilot was flying from the left seat to gain experience prior to being checked out and I was in the right seat. The weather was good, but due to a high overcase the night was very dark. Being over enemy territory as well as a sparsely populated area, there were few lights on the ground for reference. I saw what might have been the cluster of code lights which was to identify our target. I took over the controls and started a moderate bank to the right, referring to the flight indicator of the A-4 automatic pilot to control the degree of bank. Being intent on identifying the target, I inadvertently increased the degree of bank to a point where the flight indicator spilled (approximately 50 degrees). Unaware of what had happened, I was momentarily confused at the strange gyrations of the flight indicator and had started into a spiral before I realized what was going on. I righted the ship by referring to the needle and ball. Neither the ship nor the crew was damaged."

Using an Inoperative Tachometer.

"A pilot took off in a P-47 with a full wing tank combat load and his tachometer read only 500 RPM at full takeoff power. He thought that he was only getting 500 RPM so he pushed his prop pitch and throttles into emergency position and still couldn't pick up on his speed. Rather than cutting back on his power to try to determine whether it was his tachometer or his prop not turning up, he completed a circle of the field, came back in and landed. He found out that he actually was turning up over 3000 RPM, for a period of about three or four minutes. He should have noticed this malfunction going down the runway but apparently he was watching other planes in the area."

Using an Inoperative Remote Compass.

"The radio operator in a C-47 turned off the inverter switch and did not notify the pilot. I, as pilot, was using the remote compass and did not realize that the radio operator had turned off the inverter until we were considerably off course. The radio operator claimed later that the inverter was creating a disturbance of his reception on the liaison set."

Conclusions and Recommended Research.

The frequency with which pilots report using an inoperative instrument is

sufficient to indicate that a special effort should be made to design instruments in such a way that an indication is given when the instrument is inoperative or malfunctioning. Such indications, if successful, would greatly increase the pilot's faith in his instruments.

Suggestion 9. Warning flags or other devices should be built into aircraft instruments, whenever feasible, to indicate to the pilot that the instrument is inoperative. Gyro instruments should have a flag to show when the gyro has tumbled as well as when it is caged.

X. Scale Interpretation Errors.

Six percent of the instrument reading errors collected in the present study resulted from difficulty in reading between numbered graduations of a scale or failure to assign the correct value to a numbered graduation. These scale interpretation errors are of three types: (1) misinterpreting the meaning of calibration numbers, (2) failing to associate the correct value to the unnumbered graduation marks, and (3) difficulty in interpreting an instrument because of an unfamiliar dial. The latter type are a somewhat special case in that they are transition errors and have something in common with the transition errors discussed in the substitution category. Typical descriptions of scale interpretation errors are quoted below.

Misinterpreting the Airspeed Indicator Scale.

"The conditions of this flight were as follows: night, visibility 1/2 mile, ceiling about 100 ft., runway very wet, 20 MPH cross wind. The pilot was taking off on a combat mission with a gross weight of about 68,000 lbs. The aircraft, was equipped with an airspeed indicator of the type that has numerals for every 50 MPH instead of every 10 MPH (i.e., 100 - 150 - 200, etc. with marks to indicate 110 - 120,-etc.) The pilot misread the instrument and thought he was flying much slower than he actually was, consequently did not climb as fast as he should have. The aircraft struck a tree causing major damage to No. 3 engine and a fire quickly ensued. The pilot was able to jettison his bombs and gain enough altitude for his crew and himself to bail out before the aircraft exploded. Most of the crew landed in the water and couldn't be picked up until daylight several hours later. Fortunately, none of them suffered more than minor injuries."

Unfamiliar Setting of Rotatable Airspeed Dial.

"I was in an old C-47 with the type airspeed indicator that could be moved and set at any position. In our squadron we had an SOP whereby we always kept the airspeed in a certain position, and in that way when we had to get off quickly we didn't have to check the cockpit completely. I started out one day while being strafed so I gave it the gun and away I went. The pilot before me was a new boy and had changed the setting on the airspeed instrument. I hit a bump in the runway and thought I could hold it in the air because the position of the needle was where it usually was at 85 MPH. I called for gear up. As the copilot reached for the gear, I began to mush. I checked my airspeed more closely and found I had only 60 MPH. I did manage to keep my gear down but it was one

of those near misses. I think that type instrument is not used in the newer ships but with the instrument down where it is not easy to check and having been moved, it almost caused me to crack up a C-47."

Misinterpreting a Numbered Graduation on the Directional Gyro.

"The student was on a scheduled cross-country in an AT-6, the first leg of which was 30° . Student took off and misread his gyro compass, setting the "30" which is 300° under the lubber line instead of the '30'. Being unused to aerial navigation, he misread his map and in a short time became thoroughly lost. This is a typical case which is not unusual even among more experienced pilots."

Analysis of Scale Interpretation Errors.

Errors in reading between numbered calibrations may occur because there are insufficient graduations on the dial, because the numerical value represented by each graduation mark changes from one portion of a dial to another, or because of lack of uniformity in the kind of scale markings used on different dials. Some airspeed meters offend in both the latter ways. Scales in which the scale markings are other than units are probably especially subject to this type of reading error.

Difficulty in interpreting an instrument because of the unfamiliar dial were most frequently reported as involving the airspeed indicator. Fuel gages and compasses were among the instruments mentioned less frequently. In most cases, the difficulty was experienced in reading or interpreting a non-uniform type of dial.

The meaning of calibration numbers is sometimes misinterpreted. This error usually involved the directional gyro and can occur only for courses of 0° to 36° . For example, the pilot determines that his heading should be 21°, but flies a course of 210° because he fails to remember that the last zero has been dropped from numbers stamped on the compass card.

Conclusions and Suggested Research.

It can be concluded that interpretation of the meaning of scale marks and of the meaning of abbreviated numerals at major graduation marks on a dial is a source of error in using aircraft instruments. No scientific remedies can be suggested for this difficulty until further research can be conducted on the problem.

It is suggested that research on the problem of scale interpretation be directed at determining sources of confusion in interpreting scales with graduation marks at intervals of two, five and other non-unit values. Attention should also be given to sources of error in using non-linear scales. The confusion in using scales other than those marked off in units, tens, or hundreds, must be weighed against the possible loss in precision from using fewer graduation marks. One alternative to the use of condensed scales is to go to a multi-revolution instrument. However, evidence reported on errors in reading multi-revolution instruments indicates that this is not a good solution and should be avoided, if at all possible.

XI. Illusory Body Sensations Leading to Disbelief in Instruments.

Difficulties in instrument flight sometimes arise when there is a conflict between false sensations of attitude or rotation arising from sense organs within the body, and the true indication of the aircraft instruments. 5 percent of reported error experiences involved this factor. Two typical descriptions of this type of error are quoted below.

Illusions during Formation Flight through Clouds.

"While flying in a formation of C-47's, we had to climb through a dense overcast. At one time during the climb, I happened to get on a lower level than the lead plane and experienced a sensation that he was rolling over the top of me. Immediately, I began checking my own instruments to see that I hadn't gotten into a steep bank or a spiral all of a sudden and found that we were still climbing on a straight and level course, yet the effect on me was the same as if we were in a steep spiral or turn. Immediately upon turning back on the level slightly above his plane, the effect went away."

"This is an account of my experience with vertigo in flying the right wing position in a B-24 in combat missions during the times when we were taken through clouds. Most generally, it was the policy not to take us through anything heavier than thin sirrus, which compares to fog, but many times we got into cumulus, which proved to be pretty dark and rough on the inside. It was really a physical labor to keep your airplane in formation with the leader even when you were right on top of him. You had to fly very close to him or you would lose him completely. Your greatest safety was to stay with him in formation. My experiences were rather bad because of the vertigo that I experienced and the sensations that were involved. I was unable to watch my instruments enough to convince myself that we were not doing acrobatics. I was flying formation abreast of him and my head was twisted 90° from my body, causing me to feel that we were doing slow rolls to the right all the time when I was flying right wing position. I would check back with my instruments to see that my airspeed was all right and that I was not turning but I would check only for a glance and then would have to watch him again. There was just not enough time to convince myself that I was not turning. The greatest danger was that I would lose my coordination of flight. I would start holding away from him with my rudder and start tipping into him with my wing. I couldn't judge my own attitude and, unless I concentrated to an extreme, I would get the airplane into a forward slip. This loss of coordination is pretty bad in rough weather because other things can happen as a result of it, such as getting into a spin without much difficulty if your airspeed is low."

Analysis of Illusion Errors.

False body sensations probably occur much more frequently during flight than is generally believed. In a study reported recently by the Aero Medical Laboratory (see reference 9), it was found that after thirty seconds of level flight without any direct vision approximately half of the pilots reported that they were in a turn.

In contact flight, and also in instrument flight carried out under favorable conditions, the pilot is hardly aware of these false sensations since he unquestioningly accepts the evidence of his eyes. However, under certain flight conditions, the conflict becomes much stronger. In a recent report (see reference 12) of data collected from 147 combat returnees, the incidence of disorientation while flying was found to be related to weather factors such as flying in the overcast, at night, in haze and with the horizon invisible; to formation flying factors, particularly flying wing; to "personal" factors such as division of attention, excitement and fatigue; and to sensory stimulation factors, such as doing acrobatics or flying with the head turned to the side.

Conclusions and Recommended Research.

It can be concluded that illusory sensations of body position are most likely to interfere with instrument flying when the pilot is unable to devote full attention to his instruments. Additional research is needed, however, to determine more precisely the exact conditions under which such difficulties are likely to occur.

The most likely method of eliminating this type of error is to design instruments that can be checked more quickly, and that give indications which are so easy and "natural" to interpret that the instruments will provide a stronger stimulus than the pilot's body sensations.

XII. Forgetting Errors.

A forgetting error involves failing to check visually or properly refer to an instrument before takeoff or during flight. In many error descriptions, it is difficult to distinguish between forgetting to use a control and forgetting to check an instrument. In the present series of reports forgetting to uncage gyros, forgetting to turn fuel quantity gage indicators to the correct tank, and similar errors which involve setting or adjusting a control are treated as control errors. Probably for this reason, the frequency of forgetting errors in reading instruments is relatively low, accounting for 4 percent of the reports gathered in the study. For a discussion of similar forgetting errors in using controls, the reader is referred to Memorandum Report No. TSEAA-694-12, dated 1 July 1947. Typical accounts of forgetting errors in checking instruments are quoted below.

Forgetting to Check an Instrument Before Takeoff.

"I was first pilot and was making a cross-country flight in an AT-6 from southern Texas to South Carolina through several warm fronts. Prior to taking off, I neglected to check my instrument panel properly. On the first leg, I used the radio station and beam bracketing system and had no difficulty. Later in the day, on the last leg of the trip (especially good weather), a newly graduated pilot who was flying with me took off and made the same error (failure to check the instruments). We ran into unexpected weather and the suction was very low which caused inaccurate instrument readings. When I became aware of this, we were in a spiral and approximately 1000 ft.from the ground."

Forgetting to Check Directional Gyro During Flight.

"Three P-51's took off from Williams Field heading for Salt Lake. The lead aircraft took up a heading 40° left of course and kept insisting he was heading for Salt Lake when questioned. When asked outright, he had not set his directional gyro with his magnetic compass. This pilot had over 1000 hours at the time."

Analysis of Forgetting Errors.

Two types of instrument forgetting errors were reported with approximately equal frequency. They are (1) forgetting to check visually an instrument while executing the pre-takeoff or pre-landing check, and (2) forgetting to cross check from one instrument to another during flight. The former would be minimized or prevented by correct use of the check-list which apparently is infrequently or incorrectly used. Forgetting to cross-check involves such things as failure to reset the directional gyro to correspond to the magnetic compass and is usually less serious than errors made during the pre-takeoff check.

As was pointed out in an earlier report (see reference 6), forgetting is a psychological phenomenon that may occur for a number of reasons. In most cases, pilots have well established habits which normally enable them to carry out cockpit procedures more or less automatically without much thought or deliberation. Forgetting is most likely to occur when something happens to interrupt or momentarily distract the pilot from his normal routine. Sometimes even a special effort to be more careful than one's habit may in reality turn out to be a distracting or disorganizing influence.

Pre-takeoff and pre-landing checks are lengthy procedures involving a series of reactions. It is easy to omit a part of the sequence if the job follows no logical pattern, or if there is no easy method of check reading after the job is completed.

Conclusions.

It will never be possible to eliminate all forgetting errors, but is believed that the following suggestion is warranted as a means of reducing such errors.

Suggestion 10. Develop a simplified mechanical check-list which will give the pilot an easier reference for check reading to determine when everything is "O. K. for takeoff" or "O. K. for landing", and make it impossible to omit an item.

XIII. SUMMARY

1. The purpose of the present study was to discover and classify the types of errors made by pilots in interpreting aircraft instruments.

2. A total of 270 error-descriptions were collected. These were sorted into nine major error categories.

3. Only a few of these errors are of such a nature that equipment design changes necessary to reduce the frequency of their occurrence are obvious. In this respect, difficulties in using instruments pose a greater variety of problems for research than do errors in using aircraft controls.

4. The principle research problems indicated by the present investigation are the following:

a. Discovery of more satisfactory methods of display for information, such as altitude data, that calls for the use of excessively long scales.

b. Tests of the hypothesis that one of the most important factors in insuring the proper interpretation of instrument displays is the use of a uniform direction-of-motion principle for all instruments.

c. Tests of the hypothesis that the cockpit reference principle is optimal from the viewpoint of pilot efficiency in interpreting instrument displays.

d. Development of improved warning devices and other means of conveying signals including methods of indicating that particular instruments are inoperative.

e. Study of the variables influencing instrument legibility and determination of the degree of reading precision possible with different styles and sizes of dials, scales, pointers and numerals.

f. Development of a practical system that will insure positive identification of different instruments under night lighting conditions.

g. Study of scale design features favoring easy transition from one scale to another with minimum confusion between dials on which graduation marks signify different values.

5. In addition to the error categories developed for the present data, it is known that many other difficulties are encountered in interpreting instruments. Some of these problems are not mentioned by pilots because they do not lead to specific errors. In other cases, the problems relate to new techniques, new procedures or new display methods that are not generally known to pilots. These problems indicate work in the following research areas:

a. Development of practical combined or simplified instruments that will eliminate some of the mental steps required in interpreting present instru-

ments.

b. Comparison of pictorial versus symbolic instrument presentation.

c. Study of instruments that present on a single dial both a primary condition and the first or second derivatives of this condition.

d. Comparison of visual and auditory channels for displaying different types of information.

e. Determination of optimal pattern arrangement of instruments on the panel.

f. Study of instrument lighting for night use in relation to instrument legibility, eye fatigue and night vision.

6. The solution of these research problems will require a major effort over a period of years by scientists trained in the study of human perceptual and mental processes. Their solution is becoming increasingly important, however, for as the speed of aircraft increases, the time interval during which the pilot must see, comprehend, and act becomes less and less, and the penalties for errors more severe.

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