# Aviation Research

## MONOGRAPHS

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# Foreword

It is paradoxical that Alexander Coxe Williams, Jr., who was honored a year before his death at age 48 by the first Franklin V. Taylor Award for an outstanding career in engineering psychology, published no books, only 11 papers in professional journals, four of which were in another field, and approximately 21 readily obtainable government reports. The following collection of previously unpublished papers might have been presented simply as *Early Alex*. A suitable subtitle, for the private amusement of his former students, might have been *The Truth*. The Navy people from the former Special Devices Center at Port Washington, Long Island, would recognize the pieces most readily as *Task Order Sixteen*, the casual identifier for SDC Human Engineering Project 20-L-1; Contract N6ori-71, Task Order XVI; Project Designation NR-784-003.

By whatever name, the words that follow document the emergence of a brilliant young psychologist and World War II Naval Aviator as the father of the systematic, as opposed to topical, study of human factors in aviation equipment design and constitute his essential written statements on the subject. These papers written between 1947 and 1949 at his Aviation Psychology Laboratory served as the original charter for the Illinois school of aviation psychology. Within them also can be found the theoretical foundations used to justify the embryonic Army-Navy Instrumentation Program a few years later.

The fact that Alex wrote these papers at all is a tribute to the efficacy of the requirement, already prevalent in the late 1940s, that technical progress reports on contract research be submitted every so often, whether or not the investigator has made any technical progress. Whenever Clifford Seitz, his perennial contractual benefactor from the Special Devices Center, notified him that a report was overdue, Alex would sit down and commit to paper whatever happened to be the current topic of discussion at the lab. Alex wrote the way he spoke, simply putting thoughts down on paper as he would say them. Lib Turnock would type them on mimeograph stencils without editing and run them off after only the most casual proofing. That was the only form in which they were ever to appear prior to the advent of the copy machine. As a consequence, his reports were, in effect, conversations presented in monologue form.

In editing these papers, Bill Schmidt and I have tried to preserve the essentially conversational qualities of Alex' writing. We have cleaned up the obvious errors he did not bother to correct. We have attempted to clarify a few obscure statements and lines of thought, and we hope that we have not distorted his intended meaning. If we have, some of the disciples will be heard from.

By example, Alex repeatedly demonstrated the power of scientific analysis and experimentation in bringing order to the real world of aircraft display and control system design. Months of analysis and exploration always preceded formal experimentation. More often than not he found apparent problems, upon Socratic analysis around his large conference table, to be either trivial or resolvable without recourse to experimentation. Only questions whose answers could not be determined by other means were submitted to experimental study. The papers that follow are early examples of that process and, more than any others he wrote, set the course he and his students were to follow.

STANLEY N. ROSCOE
*Editor*

# Preliminary Analysis of Information Required by Pilots for Instrument Flight

INTERIM REPORT 71-16-1, APRIL 1947

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## STATEMENT OF THE PROBLEM

If it could be known exactly what information a pilot requires in order to fly on instruments, then ways could be devised for presenting him with this information in the most efficient manner. It follows by implication that without first knowing what information is required, a great deal of time and effort might be wasted devising means for presenting information which actually is unneeded. This is not only a matter for speculation. We intend to show that many instruments now in common use are actually superfluous. Assuming for the moment that efficient ways for presenting information could be devised as a result of research and analysis, the problem comes from the phrase, "what information a pilot requires in order to fly on instruments." Reflection will show that the statement is not complete since it is evident that the information required will vary depending upon the kind of flight contemplated. But the real problem occurs from the use of the word *information*.

Information implies description and definition, and there is always a variety of points of view from which to describe and define. What one man calls a house, another calls a home, while still another considers it an investment, and a fourth may look at it simply as a collection of building material or an object of art. It cannot be denied that it is possible for the same house to be all of these things and many more at the same time. Likewise, the information required by a pilot in order to fly on instruments is susceptible to many alternate definitions.

Words are symbols, and it is only in rare cases (as in a GCA approach, for example) that words constitute the effective and immediate embodiment of the information required by a pilot.

Most often he uses visually perceived relationships between objects or indicators. He also uses auditory, kinesthetic, and vestibular cues. When one attempts to verbalize this type of information for purposes of analysis, the greatest danger occurs from the natural tendency to abstract. Verbal abstractions are easily carried to the point at which they lose touch with their referents and hence become nonoperational. When that happens, any conclusions or recommendations achieved are simply not applicable to the initial or true situation. There is no common ground between the two.

For an example of abstraction in the case of flight information, consider the concept of direction. Direction is an abstraction. It is true, and few would be willing to deny, that since an aircraft moves, its pilot requires information concerning the direction in which it is desired to or does move. Yet, what are the real referents to this term; what is its actual meaning at the operational level? Consider the case of a cross-country pilot. He needs to know in what direction to fly. If he had a compass, direction could be given him in terms of compass heading. If he had a radio compass, it could be given in terms of pointing right or left. If he had a radio tuned to a radio range, he could follow the auditory beam. If he could see the ground, he could use pilotage and follow landmarks. But to be given a compass heading without a compass or a radio range without a radio or a railroad track without being able to see the ground would not solve the pilot's problem at all. It is not informative simply to say that a pilot requires directional information. Sooner or later it must be decided, in very specific terms, what kind or kinds of directional information he needs, and that is where the real problem exists.

On the other hand, just as abstraction may cause the analyst to miss the real issues, so also a too specific description may result simply in an endless enumeration of details at a sensorimotor level. It can be argued that what the pilot really needs to know is how to move the controls. He needs to know when to move which control, in what direction, how much, and how long. If he knew these things, then he would be able to make a flight.

Description at the motor-response level is possible, but it would be unproductive since it would completely ignore essential factors operating at more generalized descriptive levels—things such as the weather, the contour of the land, and the purpose of the mission. The problem then is to discover levels of description that are neither so abstract as to be uninformative at the operational level nor so specific as to miss factors operating as generalizations. This is a purely semantic and not an aeronautical problem. The factors, both specific and general, which together result in an actual flight, do so whether they are verbalized and described or not.

Furthermore, it is difficult to see how the effective factors in instrument flight, in principle, can be different from those in contact flight. The flight characteristics of the aircraft are identical in both cases, and the end result is much the same. The instrument pilot must know essentially the same information that the contact pilot must know. But the specific forms of the information may be, of course, quite different. For the time being, we will treat instrument flying as a special case of flying in general and will attempt to analyze the information required by a pilot just in order to fly, without assuming anything with regard to either contact or instrument conditions.

## ANALYSIS OF THE PROBLEM

Between the knowledge of what control movements to make and the knowledge of the purpose of a mission lie all the areas of information which together result in the accomplished flight. Since the only course of action open to a pilot is through manipulation of the aircraft controls, it follows that all the information he receives must eventually be filtered down to this level in order for him to participate in the flight at all. These pieces of information somehow work together in an organized way and, for purposes of analysis, must be fitted into some descriptive pattern. The parameters of this pattern are unknown, but at least it can be said that a basic requirement is that they must be independent of any specific flight instrument or type of instrumentation (as well as contact cues). Pilots do fly successfully either on instruments or contact; therefore, they must be receiving the proper information. Consequently, the temptation is strong to structure and describe essential information in terms of what is known already to work, namely, modern instruments. Thus, the first problem is to break away from the notion of specific ways for presenting information; the second, to try to develop a scheme into which all pieces of information will fit in a logical way.

From the various schemes available for the analysis of complicated behavior, we have chosen one that seems to give us considerable insight into flying (Muenzinger, 1942). This scheme asserts that out of a continuous and varied stream of behavior, any particular sequence can be considered as a unit if it is directed towards a given goal. Such a sequence has a start, S, and an end, E. It can be symbolized thus: S ⟶ E. Each S ⟶ E is distinguished from every other S ⟶ E by the goal, G, which brings it into being in the first place. The goal determines what occurs between the S and the E. The activities of the person who is behaving can be said to be goal directed: that is, his actions can be understood as an attempt to achieve a goal, and only in this light do they belong together as a related sequence with a definite start and a definite end. The end occurs when the goal is achieved or else when it is abandoned for another goal as the case may be. The scheme goes on to say that in order to achieve a goal, the behaving person must make a series of discriminations between those courses of action that will lead him to the goal and those that will not and that he must, of course, select those that will lead him to the goal. Finally, having selected the proper courses of action, he must then be able to execute them, that is, turn them into an actual and adequate motor performance.

This is a straightforward and compact scheme, and it seems reasonable to expect that it might be applied with success to the flight situation. We can consider any flight as an S ⟶ E sequence of behavior; it is goal-directed. The events which occur during the flight become meaningful when the purpose of the flight is understood. The purpose or mission of a flight, for example, explains why one plane is seen doing aerobatics, while another is observed circling over town, and still a third flies across the sky in a straight line until out of sight. Every flight has a start, S, and an end, E. Furthermore, the range of this scheme starting with the goal, G, and finally ending with a series of motor performances exactly fits the range of data which we have said constitutes the spectrum of flight information; that is, all information lies between the knowledge of the mission and the knowledge of how to move the controls.

With this promising start, let us see what happens when we apply the remaining characteristics of this scheme to the flight situation. The scheme states first that in order to achieve a goal, the behaving person (the pilot) must make a series of discriminations among courses of action open to him, selecting those that will lead him to the goal, and second that he must translate these courses of action into aircraft performance through the manipulation of controls.

## Discrimination

First of all, let us attend to the process of discrimination. What courses of action are open to a pilot? He can do many things, but we suggest that (1) since his goal is always related to him directionally, he is obliged to make a directional discrimination; (2) since his goal is always related to him via the air, he must make a height or altitude discrimination; (3) since his goal is always related to him in time, he must make a temporal discrimination; (4) since his goal is always related to him via the continuing performance of his aircraft, he must make a mechanical discrimination. These discriminations, or course-of-action selections, we shall designate as sub-goals, or indices of desired performance.

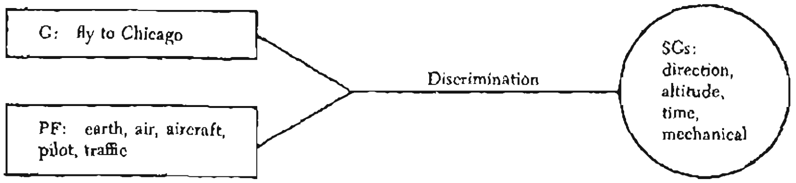
We will contend that these four sub-goals are both necessary and sufficient for achieving any flight goal. Necessary means that in order to achieve a goal, each discrimination must be made; sufficient means that no additional discriminations are required when these are made correctly. In other words, a pilot can achieve any flight goal provided he flies in the proper direction at the proper altitude for the proper time and with a properly functioning aircraft.

The question arises now concerning what information a pilot needs in order to set up these sub-goals, SGs, for his particular flight. Analysis suggests that there are only five independent sources of information pertinent to flight and that all other information a pilot may receive is important only because it stems from one of these five sources. They are: (1) the earth, (2) the air, (3) the aircraft, (4) the pilot, (5) other aircraft. In the process of discrimination, what the pilot does is to consider each of these five variables in the light of his goal or mission. This leads him to specific conclusions as to what each sub-goal must be in order to make a successful flight.

The earth contributes to this process because some parts of its surface, such as cities, airports, and rivers, are of differential significance compared with other areas of its terrain. The air is important because it is the medium in which flight occurs. It moves across the surface of the earth and contains weather of various sorts, some of which may influence flight. The aircraft contributes because of the limitations implied by its performance characteristics. It has certain speeds at which it flies and certain rates of climb. It has a service ceiling and is limited in the load it can carry. Its range varies as a function of its load and its fuel aboard. Any characteristic which is built into the aircraft or has been caused by damage to the aircraft qualifies in this category and helps determine the pilot's sub-goals in some way.

The pilot helps to determine the sub-goals because he, too, has his own characteristics and limitations. He may black out or become hypoxic or fatigued. He responds more adequately to some stimuli than to others. His ability to learn and respond have their own patterns. His training may be more or less adequate. All these things must be considered when setting up sub-goals designed to accomplish a mission. Finally, other aircraft, or traffic, enter into the process of discrimination since collision would most probably terminate any flight. Or, should the mission be to intercept enemy aircraft, the behavior of the enemy plane would most directly influence the pilot's sub-goal decisions.

It goes without saying that since any particular sub-goal in a sense represents the pertinent aspects of these five variables, it remains valid only so long as the variables from which it was derived remain the same. If we call these five basic variables the physical facts of flight, PFs, and the mission the goal of the flight, G, then we can represent this relationship as follows:

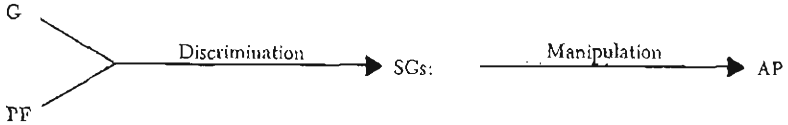


Any changes in either G or PF will result in some change in the SCs. A change in PF may result in a change in G should it turn out that, as a result of the change, successful discrimination is no longer possible. A change in G will result in a change in PF in the sense that PF must be reviewed in the light of the new G. Of the five categories of PF, three are likely to change frequently enough to warrant the pilot's being supplied with continuous information concerning them. Those are the air, the aircraft, and traffic.

Let us sum up what we have said so far from a slightly different point of view. A flight is a goal-directed S——→E sequence. It is accomplished according to a certain procedure. First, the pilot is required to make a series of discriminations which result in setting up four sub-goals. Then he must translate them into action by manipulating controls. If all this has been done correctly, the mission will be achieved. These discriminations may be made before the flight starts. But because some of the facts upon which the discriminations are based may change during the flight, the pilot must be kept aware of any changes that occur. The process of discrimination, therefore, must be carried on throughout the entire flight.

### Manipulation

When the sub-goals are set up, they are then translated into aircraft performance, AP. This requires motor activity on the part of the pilot, which we shall designate by the term manipulation. Schematically the entire procedure looks like this:



Manipulation means that the pilot acts (moves the controls) in order to make good a course, make good an altitude, make good a temporal progress to G, and maintain proper mechanical operation of the plane. The way he does this is specified by the nature of the controls he must move. Controls have their own characteristics, and because of that the pilot needs certain definite information in order to manipulate them. Consider, for example, the three basic flight controls: a stick or wheel to control the ailerons and elevator, foot pedals to control the rudder, and a throttle to control thrust. Two of the three, the stick and rudder pedals, have neutral positions. They can be moved a small amount or a large amount, quickly or slowly. Their movements can be held a short time or a long time. In actual practice, there occur certain repetitive patterns of control movement associated with the various elementary maneuvers such as turns, for example. The decisions concerning control movement listed below refer to these patterns. Although the pilot does not normally make these decisions consciously, each must be made implicitly, and for each the pilot must receive appropriate information:

1. When to move the controls
2. Which control or controls to move
3. In which direction to make the movements
4. How much to move (in the sense of how large a movement pattern to make)

5. How long to move (in the sense of how long to continue the effect of a movement pattern)

How the pilot makes these control manipulation decisions depends upon how the information concerning the sub-goals is presented. Sub-goals are presented through the medium of displays which may be either contact or instrument in type. The mechanism for presenting the information which covers the five control-movement decisions usually consists of a pair of indices, one of which represents the desired performance of the aircraft, or sub-goal, and the other, the actual performance of the aircraft. To make good a sub-goal, the pilot brings these indices into alignment by moving the controls. The ability of the pilot to bring about an alignment depends upon the ease with which the moving index can be positioned. This in turn depends upon how well the movement of the index informs the pilot concerning each of the five control-movement decisions. He uses the perceived movement of the index to guide his movement of the control.

Let us see how this works. Suppose that the direction sub-goal is displayed to the pilot as a magnetic compass heading. A given heading mark on the compass card represents the index of desired performance. The lubber line represents the index of actual performance. The two must be brought into alignment by moving rudder and ailerons. Does this display tell the pilot everything he needs to know about moving these controls? In the first place, it does not tell him completely about Decision 1, when to move the controls. If there is an initial misalignment, that is a positive signal that the controls should be moved. But as an alignment is effected, the controls must be moved again, and there is no positive signal to say when this should be done. With respect to 2, which controls to move, the display does provide this information. It also provides information concerning 3, the direction of movement. With respect to 4, how much to move the controls, the display provides no satisfactory information. The magnetic compass has a turning error, and because of this it provides no usable cues concerning rate of turn or angle of bank. Thus, the pilot cannot tell by looking at the magnetic compass how much to move ailerons and rudder. For 5, how long to move the controls, the problem is similar to 1. Because of its turning error, the magnetic compass does not tell the pilot when to start stopping a turn. In order to compensate for these deficiencies in the magnetic compass, the pilot is commonly provided with a turn indicator for 4 and a clock for 5.

In addition to the necessity for providing information about each control-movement decision, it makes a difference how this information is presented. For example, suppose the pilot has a directional gyro in addition to the magnetic compass. Disregarding precession for the moment, the directional gyro has no appreciable turning error and hence does provide information covering all five decisions. But in the case of 4, how much to move the controls, it offers a poor cue, one that is difficult to use. The cue for "how much" is the rate at which the indicator revolves past the lubber line. Rate of movement is difficult to perceive as such. Large changes in rate can occur before being perceived. This results in chasing or under- and over-controlling. There is no desired rate with which the actual rate can be compared. What is needed here is a reference index, an index of desired rate with which the index of actual rate may be aligned. Such pairs of indices are provided in the rate of turn indicator or the angle of bank indicator, and consequently these instruments are used in addition to the directional gyro to provide the information concerning how much to move the controls.

We can conclude, then, that a display must, either by itself or in conjunction with other displays, cover all five control-movement decisions and that for each decision a pair of indices must be provided, one of which represents desired performance and the other the actual performance of the aircraft. We can further suggest that one display providing all this information is superior to several displays each providing a part.

## THE FORM OF THE SUB-GOAL

Just as the directness of presenting sub-goal information facilitates control-movement decisions and minimizes the difficulty of the pilot's manipulatory task, so also does the directness of relationship between sub-goal and G/PF affect the difficulty of the discriminatory task. The best form a sub-goal can take is the direct display of the aircraft and G/PF on the same perceptual continuum as is the case, for example, in contact flight when the goal is within sight. Such a display is not always possible. When it is not, then some index which stands for the direct relationship is used for the sub-goal, for example, a magnetic compass heading. The number of variables that go into the derivation of a sub-goal index is a good measure of its value. The more variables that enter in, the less adequate the indicator is. Let us take three contrasting examples to see how this is so.

We will first derive a directional sub-goal in the form of a magnetic compass heading. In this example, the directional relationship between airplane position and G plus the pertinent PF is not directly perceived. Instead, it must first be represented on a chart. Here the direction relationship between aircraft and G is translated into a desired course relative to the North Pole, or degrees from true north. True course is then changed into compass course by applying variation and deviation. Compass course is changed to compass heading by correcting for drift. Drift is sometimes perceived directly through a drift meter, but more often it is obtained from a weather report on winds aloft. This in turn requires a knowledge of altitude and position. Altitude is not directly perceived but depends upon an altimeter, which in turn depends upon barometric pressure and temperature. And so it goes. The list below shows the major items of information involved plus the equipment needed to supply them:

*Information*

- True course
  - Variation
  - Deviation
- Compass course
  - Wind direction
  - Wind velocity
  - Drift
- Compass heading
  - Altitude (indicated)
  - Barometric pressure
  - Temperature
- Position
  - Airspeed
  - Time (hours, minutes, seconds)

*Equipment*

- Chart
- Plotter
- Pencil
- Computer
- Weather report
- Compass
- Altimeter with pressure setting
- Airspeed indicator
- Thermometer
- Clock

In spite of the fact that the pilot must make this series of discriminations in order to derive his directional sub-goal, the compass heading would be adequate if the variables entering into its derivation could be measured precisely and if they didn't change during flight. However, many of these variables are not measured precisely, and, as we pointed out when discussing PF, some of the factors do change, forcing the pilot to rederive his sub-goal from time to time. Consequently, the magnetic compass is a poor device for presenting a directional sub-goal.

Next, let us consider the radio compass as a directional sub-goal. Assuming for the moment that the instrument works satisfactorily, it provides a better sub-goal than the magnetic compass because there are fewer variables standing between it and the actual directional relationship. It points directly to the goal and, therefore, eliminates the need to interpose degrees from true north, variation, and deviation. It must be corrected for drift, but it provides its own cue for this correction and, therefore, does not depend upon knowledge of wind direction and velocity or other subsidiary items needed to derive compass heading.

Finally, let us consider a third form which the directional sub-goal might take. In this form, the sub-goal is simply a chart on which the goal and the position of the aircraft are displayed on the same perceptual continuum. Here, the relationship between the two is directly perceived, subject only to any corrections required by the construction of the chart. No other intermediate steps are necessary.

### Two Requirements for an Adequate Sub-goal Display

It should be clear now that any instrument designed to present a sub-goal should, if possible, meet two requirements. It should be related as directly as possible to the direct perception of the sub-goal in question (direction, altitude, time, mechanical operation), and it should inform the pilot adequately concerning each of the control-movement decisions he must make. Failure to meet either requirement will always result in the necessity for including supplementary information. This in turn means extra instrumentation of one type or another depending upon which requirement is lacking. As a result, the pilot's task will become more complex than it need be.

### The Altitude Display

If our scheme as presented so far has any validity, we should be able to use it to explain the function as well as the complexity of contemporary instrumentation. We have already done this indirectly in the case of the directional sub-goal. Where the directional sub-goal is represented by a compass heading in today's cockpit, we have seen the host of additional information needed to bridge the gap on the discriminatory side between the compass and the actual directional relation between the aircraft and G, the goal of the mission. On the manipulatory side, our examination of the shortcomings of the compass explained why the rate of turn indicator and clock (or artificial horizon and directional gyro) are included on the instrument panel to supply the information the compass is unable to give. But the value of our scheme does not stop there; it permits us to predict how improvements in a sub-goal presentation can be made. It tells us what requirements a good presentation must meet. To carry on the argument we will discuss how other sub-goals are presented in today's cockpit in order to see what insights we may gain concerning the inadequacies that exist.

The altitude sub-goal is represented in today's cockpit by an altimeter. On the discriminatory side, this representation is not altogether inadequate. In the first place, the direct perception of altitude where aircraft, G, and PF (terrain for the most part) appear on the same continuum is not in itself precise except when the plane is close to G. The first derivation from direct perception would be a statement of the number of feet above ground level necessary to clear the pertinent terrain and within the requirements of plane, pilot, and traffic. But since this cannot be directly perceived in all cases, the next derivation involves a statement of the number of feet above a common standard (sea level). Feet above sea level can be measured fairly precisely at least as far as G and PF are concerned, and since G and PF usually do not change, any sequence of sea-level altitude will remain good throughout the flight. The drawback comes in the next derivation in which feet above sea level is translated into feet as registered by the altimeter. To do this successfully one must have knowledge of both barometric pressure and outside air temperature. Since both change from time to time and place to place, the altimeter reading loses efficiency as a representation of the altitude sub-goal. Here we see where an improvement could be made if the pilot could be provided with true altitude above sea level independent of the effects of barometric pressure and temperature. Because of this defect in the altimeter, the pilot requires frequent weather reports, a knowledge of position, a thermometer, and a Kollsman setting.

On the manipulatory side, the altimeter as a means for presenting a sub-goal is a terrible example of instrumentation. But it is not all the fault of the altimeter because the controls themselves are not adapted to their function in this case. By applying our scheme we shall see how well the altimeter informs the pilot concerning the required control movement decisions and, where it fails, what supplementary pieces of information are brought to its rescue. In the first place, does the altimeter tell the pilot which control to move? The answer is no, it does not. Altitude is manipulated using either one or both of two controls—elevator and thrust (throttle and propellor control, which we will consider together for convenience, although the fact that there are two of them, each with a different indicator, further complicates manipulation).

In order to decide which control or controls to move, the pilot must know, in addition: (1) how much thrust is required for the desired altitude performance, and whether or not the engine is delivering at the moment more or less than the desired amount and (2) the angle of attack, usually presented in the form of airspeed. The altimeter does inform the pilot, after a fashion, when to move the controls, but it does not always inform him in what direction to make the movement. Once again the pilot requires auxiliary knowledge of thrust and airspeed. When it comes to knowing how much to move the controls, the altimeter fails again. Once more the missing information is supplied by thrust and airspeed. But in this case, airspeed itself is a poor cue, because it is the change in airspeed and not the amount of airspeed itself that must be perceived here. Consequently, in many airplanes, information about pitch is supplied (artificial horizon). This provides a cue that is more easily perceived and more stable than change in airspeed, because it has a shorter time lag. Finally, the altimeter does succeed in informing the pilot how long to move the controls (how long to maintain a pattern of movement), since the pilot can see whether or not he has attained the altitude desired.

Of the five required decisions for manipulation, the altimeter satisfies only two. It requires a supplementary knowledge of thrust, airspeed, and preferably pitch before the pilot can make good his altitude sub-goal when represented by a conventional altimeter. Even then, the process is a complicated one. There is most certainly room for improvement here. Some means for displaying altitude must be found which also informs the pilot directly about all five decisions concerning control movement. If such were found, the need for knowledge of thrust, airspeed, and pitch would be eliminated so far as altitude control is concerned.

### The Time Display

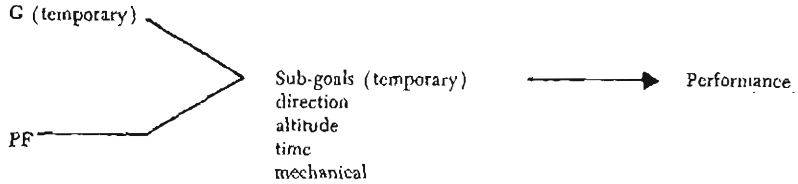
In contemporary aircraft, the time sub-goal is represented in a most indirect fashion by the airspeed indicator. The link between the sub-goal and the indicator is composed of many intermediate steps involving bits of information, such as distance, position, wind velocity, altitude, temperature, and airspeed-indicator correction, many of which are subject to changes in place and time. It is common practice in most cases not to attempt a direct control over the time sub-goal. As a result the airspeed indicator does not require extensive manipulation for this purpose. Instead, the pilot's chief concern is to keep the time sub-goal within the bounds of possibility, that is, within the radius of action (measured in terms of time) of the plane. Within that radius he is content merely to predict what the time sub-goal is from time to time. Yet, because of the deviousness of the link between the actual time sub-goal and the airspeed indicator which represents it, his predictions, in order to be accurate, require a large amount of time and effort.

On the discrimination side, a great deal can be done to improve the presentation of the time sub-goal. First, the pilot needs a direct perception of his time to G, which is automatically corrected for speed, altitude, and wind. Next he needs to know his absolute time range in a way that is corrected for changing PF. As mentioned above, manipulation is not a great problem here except in certain instances discussed later.

### Temporary S ⟶ E Sequences

Thus far, we have regarded all S ⟶ E sequences as if they were uneventful cross-country flights in which all the activity involved was directed towards the single overall goal, that of arriving at some place on the earth's surface. Not all flights are like that. During flight, many sequences of behavior occur which are obviously not directly determined by the overall goal. Oftentimes a mission cannot be described by a single goal which accounts for everything that occurs between the first takeoff, S, and the final landing, E. To illustrate this point, consider for the moment a bombing mission. The goal here is to fly to target, drop bombs, and return to base. The sub-goals that will take the pilot to the target are not the sub-goals that will return him to base. Suppose also that he encounters enemy interception on the way to target. The sequence of activities that form his evasive action cannot be described directly in terms of attacking the target. Every flight has a takeoff and a landing, but neither can be said to be specifically goal directed in the same way that the cruising portion of the flight is goal directed. For example, the direction of takeoff may have nothing at all to do with the direction of G.

The fact that flights are not uniform throughout must be taken into account in any scheme of analysis. The scheme we have chosen seems especially well adapted for understanding and giving meaning to nonconforming sequences of behavior. On the premise that all flight behavior is best understood when viewed as goal directed, it is necessary only to identify the goal in such cases in order to fit them into our scheme. Thus the overall $S \longrightarrow E$ directed toward accomplishing a mission may be subdivided into a series of temporary $S \longrightarrow Es$: $S_1 \longrightarrow E_1$, $S_2 \longrightarrow E_2$, $S_3 \longrightarrow E_3$, . . . $S_n \longrightarrow E_n$, all of which are included within the overall $S \longrightarrow E$. Every flight has at least two of these temporary sequences, the takeoff and the landing. Suppose that a cross-country pilot sees before him a line of towering cumulonimbus clouds that he wishes to avoid. In avoiding them he abandons for the time being the sub-goals pertinent to the overall $S \longrightarrow E$ and instead adopts a temporary goal, namely, flying in such a way as to avoid the clouds. He does so by adopting new sub-goals, again going through the process of discrimination and manipulation.



Thus we see that, in achieving a temporary goal, the procedure is the same as in achieving an overall goal. Goal-directed activity takes the same form in any case. There is no way of enumerating or predicting the variety of goals that may be encountered in flying. The most we can say is that, in order to achieve any goal, the pilot requires certain information about PF as described earlier and that he must set up four specific sub-goals in a form suitable for making manipulatory decisions.

## CHANGING THE GOAL

Occasionally a situation will arise in which the mission itself must be abandoned. This usually occurs because one or more PFs change in such a way that successful discrimination becomes impossible. For example, the weather at destination may close in to the extent that the landing sequence cannot be undertaken because its sub-goals cannot be set up. Or perhaps a partial mechanical failure makes it impossible to continue the original time sub-goal or set up a new one relevant to G. In cases such as these, the original G must be abandoned for an entirely new G with its attendant G/PF ⟶ Sub-goal ⟶ Performance.

When changing missions, an additional piece of information is required, and that is knowledge of position. As long as the original mission remains in force, the sub-goals will achieve G without knowledge of position, although in a sense knowledge of position, or where the flight started from, was necessary originally. In any event, when goals are changed during flight, a knowledge of position is necessary at the time the new goal is selected. The new goal is decided on by a process of discrimination in which present position, PP, is compared with current PF; thus $PP/PF \longrightarrow G$ (new).

The relevant items of information are the same as before: earth with respect to topography and geography, air with respect to weather and wind, and plane with respect to its flight characteristics, the pilot, and traffic. Likewise, the more direct the pilot's perception of PP and PF, the easier it will be for him to derive the new G. When the new G has been decided on, new sub-goals must be set up and the flight continued as before.

## SUMMARY

In summary, what information is required by a pilot in order to fly? First, he must know the mission or goal of the flight in specific terms. If need be, this goal may be broken down into a sequence of temporary goals: $G_1, G_2, G_3, \ldots G_n$. In any event, all the contemplated activity lying within the overall $S \longrightarrow E$ must be attached to some goal. If not all activities can be specifically directed toward the main goal, then the need for identifying one or more temporary Gs is evident.

Next, for each G decided on, whether overall or temporary, the pilot must be informed concerning the relevant aspects of:

1. Earth—topography, geography
2. Air—movement, weather
3. Plane—flight characteristics, including effects of load and possible damage
4. Pilot—limitations including training, present physical condition, and special instructions concerning goal of mission
5. Traffic—movement of other aircraft

Relevant means those aspects related to G.

All this information is reduced to four sub-goals that represent courses of action for the pilot to follow. These are directional, altitudinal, temporal, and mechanical. There is wide choice in the manner of presenting these sub-goals to the pilot. The manner of presentation is a question of instrumentation. How they are presented determines what additional information the pilot needs. On the discrimination side, if there are intermediate variables between the sub-goal as presented and the sub-goal as it exists in fact, then the pilot must be kept continually aware of any of these variables that are liable to change. On the manipulatory side, if the manner of presenting each sub-goal does not inform the pilot about all dimensions of movement belonging to the control in question, then additional information capable of filling the gap will be required. The pilot must be kept informed of any changes in PF that would result in changing the goal or the sub-goals, regardless of how the PFs are presented. The pilot must be kept informed of his position during flight in case the necessity arises for changing the overall goal of the mission.

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# Analysis of Manipulation

PROGRESS REPORT 6, DECEMBER 1947

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## BACKGROUND

In an earlier report, a distinction was made between the two major kinds of activities in which a pilot engages: the first was called discrimination; the other, manipulation. Discrimination is characteristically an ideational process in which the pilot selects from among many possibilities definite courses of action designed to accomplish his flight mission. The end product of this process is the setting up of four so-called independent sub-goals covering the areas of flight direction, flight altitude, flight duration, and the mechanical performance of the aircraft. Manipulation is characteristically a psychomotor process and consists of manipulating the aircraft controls in a way that will make good or execute the sub-goals decided upon. The area of instrumentation with which we are now concerned falls between these two processes. Flight instruments, on the one hand, must embody or illustrate the sub-goals selected and, on the other hand, must indicate to the pilot how to move the controls in order to make them good.

This report is concerned with the process of manipulation. Primarily it is concerned with manipulation of the direction and altitude sub-goals because these are the most difficult manipulations an instrument pilot must make. No new instrument panel would represent a great improvement if it did not make it easier for the pilot to control direction and altitude. Two questions arise: Why are these manipulations difficult, and what if anything can be done to make them less so?

## THE SOURCE OF THE DIFFICULTY

As a starting hypothesis, it can be assumed that a major portion of the difficulty stems from the controls themselves. This can be demonstrated by making a simple comparison between an aircraft with conventional controls and one that is controlled by a fully automatic pilot. In the latter case it is necessary for the human pilot only to *request* of the airplane a given performance. The request is made by pushing a button or positioning a call lever, following which the plane will automatically perform what is requested without further control by the pilot. Such control can be carried to great lengths to include takeoffs, landings, and overseas flights. Pilot manipulation is in some cases completely eliminated, and even the pilot's function as discriminator may be taken over by radio, radar, and computer. It takes no great training or skill, for example, to make a given standard-rate turn to the right by moving a lever from a position marked STRAIGHT AND LEVEL to a position marked STANDARD RIGHT TURN and then back again. But it does take a great deal of training and skill to manipulate rudder, aileron, elevator, and throttle to accomplish the same result.

Both the human pilot using conventional controls and the automatic pilot activated by call levers achieve their result in the same way, that is, by moving elevator, aileron, rudder, and so forth in proper proportion and sequence. The automatic pilot, however, is more precise and does not require training and practice. The human pilot calls upon the automatic pilot to do all precise work for him. Thus, by changing the type of control from the conventional stick, rudder, and throttle to the call levers of the automatic pilot, the human pilot's manipulation task in controlling direction and altitude is made much easier, and the difficulties normally encountered are eliminated.

In many instances it is believed desirable not to use pushbutton control. In such cases, where conventional controls are required, simplification of the pilot's task must come from improving the instruments the pilot employs as cues for manipulation of the controls. Yet because the real difficulty lies in the controls, as we have seen, it is there that the cue to instrument improvement must be found. The basic difficulties are these: control movements are not homogeneous with movements of the instrument indicators to which they belong, and movements of conventional controls do not directly or uniquely affect those aspects of flight performance in which the pilot is interested. In other words, there are no simple and direct relationships among control movement, indicator, and sub-goal.

## A CASE IN POINT: ALTITUDE CONTROL

Since altitude control is the worst offender, let us examine it more closely. From the pilot's point of view, control means either maintaining a constant altitude or climbing or descending at specific rates to other altitudes. During this performance he is also interested in airspeed, not for its own sake, but only so as not to go too fast or too slow. To accomplish such altitude performance he has available an elevator control and a throttle. In very general terms, pulling back on the elevator control makes the plane climb, and pushing forward makes it descend. It is also true, although still only in the most general sense, that adding throttle results in climb; decreasing it results in descent. However, there is no invariable relationship between stick movement and altitude nor between throttle position and altitude. Following movement of either control, the ensuing altitude response depends upon what has been done with the other control and also upon what the airplane has been doing just previously. Furthermore, although pulling the stick back at the moment might cause the plane to climb, it will not continue to climb at the same rate if further adjustments are not made. This change of response with time is true of other control movements as well.

Because the relationship between flight response and control movement is complex and variable, it is evident that the pilot cannot predict or control performance on the basis of control movement alone. That is to say, he cannot position the controls and expect certain performance to follow. Instead he has before him a group of instruments that reflect performance, and he uses the controls as needed in order to achieve certain readings on these instruments. The phrase *as needed* covers a great deal of ground. In fact, it covers all of his training and practice in instrument flying.

From studies in the Link trainer and in the air, we have found out quite a bit about the relationship between control movement and the instruments reflecting performance. Returning again to altitude control, we have found that it is possible for pilots with about 100 hours of contact flying and no formal instrument flight training to control altitude as represented solely by an altimeter, or as represented by an altimeter plus a rate of climb indicator, or as represented by an altimeter plus an artificial horizon. The results obtained by using these various combinations in the Link trainer are different from the ones obtained when these combinations are used in the aircraft. Because they are different, it has been possible to learn something about what the pilot needs to know in order to move his controls in a way that will result in the desired performance.

It was immediately evident that it is easier to control the pitch position of the horizon bar on an artificial horizon than it is to control the movement of the hands of an altimeter. The significance of this is shown very clearly on the following test: The pilot's task is to maintain a constant altitude, but for some reason he is either climbing or gliding and must return to level flight. With the altimeter, the task is to stop the needle from moving, because when it is stopped the aircraft is in level flight. Almost always the result is that the pilot does not know how much to move the elevator; consequently, when he has exerted enough pressure to stop the needle from moving one way, he has also exerted enough pressure to start it moving in the opposite direction. This results in a series of oscillations that finally become stabilized after what amounts to trial and error in manipulation. With the artificial horizon, the pilot is able to manipulate the elevator so that the horizon is brought at once in line with the reference mark and maintained there without occillation. This also results in level flight provided that both airspeed and thrust are properly adjusted. That is a large and important provision to which we will return later. But the point is now that, unlike the altimeter needle, the horizon bar can be controlled easily and accurately without trial and error manipulation.

Although the rate of climb indicator can likewise be manipulated with precision in the Link trainer, in the air this is not possible because of certain other facts that will be discussed later. It is informative to examine these differences in greater detail. Why, in the case of the Link trainer, can the horizon and rate of climb be manipulated more easily than can the altimeter? We believe that the answer lies in the nature of the relation between control movement and indicator movement. In the case of both the artificial horizon and the rate of climb indicator, the amount of elevator movement is roughly proportional to the amount of indicator movement, and the rate of elevator movement is related to the rate of indicator movement. With the altimeter, however, the amount of elevator movement is not reflected in the amount of indicator movement but rather in the rate of indicator movement, an inappropriate relationship. The rate of elevator movement shows up as the acceleration of indicator movement which for manipulation purposes is utterly useless.

There is evidence from other studies to show that the appropriateness of the relation between control and indicator movement affects efficiency of manipulation. Vince (1946) showed that in general a nonlinear relation between a control and a display is undesirable. Not quite as pertinent, another study by Vince (1945) showed that fewer errors are made when a control moves in the expected direction in relation to the movement of the indicator. Grether (1947) substantiated this finding for movements of the rudder pedal but found less difference when aileron movements were used. In the present case, it is apparently easier to estimate and respond to the extent of misalignment between indicator and reference than it is to estimate and respond to the rate of movement of a pointer.

Next it is necessary to consider the special difficulties encountered when attempting to manipulate the rate of climb indicator in the air. The fundamental appropriateness of movement as found in the Link is modified by two factors in the air.

The first is the inertia of the aircraft which comes into play whenever a change in flight performance occurs. Although this factor is simulated in the Link, it is not nearly as prominent there as in the real aircraft. It has the effect of distorting the linearity of the control-indicator relationship that even in the Link is only a rough approximation. It injects what amounts in some cases to a lag, in other cases a lead in the instrument indications, so that the movements of the indicator are not always related in the same way to the control movements that initiated them. Thus, the plane may actually be in level flight while the rate of climb needle, although in the process of returning to level, is still pointed up or down.

The second factor is, of course, rough air. Whenever the plane flies in rough air, the rate of climb indicator tends to take on a life of its own. It moves independently of any control movements. Because of the lags in the sensing mechanism, compensatory control movements are necessarily too late to be effective and result only in the need for further movements to correct the effect of the initial compensatory movements. Soon there is no semblance of an orderly relation between control movement, indicator movement, and plane performance. For these reasons, in the aircraft, the rate of climb indicator is controlled with less precision than the altimeter and considerably less than the artificial horizon.

## TWO REQUIREMENTS

Assembling the facts so far stated, the first requirement of an indicator is that its movements should be appropriate to the movements of the control to which it belongs. We have seen that in the Link this is the case with both artificial horizon and rate of climb indicators. The altitude performance obtained by using either of these instruments in conjunction with the altimeter should be approximately equal in precision and efficiency. In practice this is not the case. Performance obtained when using the rate of climb indicator is superior to that obtained when using the artificial horizon. Therefore, there must be some factor in addition to appropriateness of movement that enters into altitude control.

Most probably this second factor is the pertinency of the information provided by the indicator. As was pointed out previously, altitude performance is concerned with maintaining level flight or changing altitude at specified rates. Information supplied by the rate of climb indicator in the Link is directly pertinent to this task since it shows whether the aircraft is flying level or climbing or descending and, if climbing or descending, at what rate. On the other hand, the artificial horizon does not supply this information directly. Instead, it tells the pilot his attitude, which in conjunction with additional information can be used to infer altitude performance. For example, aligning the horizon with its reference results in only approximately level flight. A further correction must be made depending on airspeed and thrust, because the horizon tells nothing about going up and down but only about attitude. Therefore, it is evident that, although the rate of climb and horizon are equally easy to manipulate with respect to the appropriateness of their movements, the rate of climb indicator is the superior instrument for control of altitude in the Link because it tells the pilot correctly the pertinent information in terms of altitude, whereas the horizon does not.

Performance results in the air are the converse of those found in the Link. Here, the artificial horizon is superior to the rate of climb indicator for altitude control. Evidently the rate of climb, by losing its appropriateness of movement as outlined previously, has sacrificed the superiority it holds because of the pertinency of its information.

The foregoing analysis of altitude control can be duplicated for directional control; the same principles apply to both. We are, therefore, in a position to outline the requirements that instruments used in the control of both altitude and direction should meet. To repeat:

The first requirement is that indicator movement must be appropriate to control movement. Direction of control movement should correspond to direction of indicator movement. Rate of control movement should correspond to rate of indicator movement. Furthermore these relationships should be as linear as it is possible to make them, although this is sometimes impossible to achieve with conventional controls.

The second requirement is that the instruments must directly provide the information that the pilot needs in order to make good his sub-goals. If the task is to manipulate altitude, the altitude instrument should be calibrated in terms of altitude and rate of change of altitude. If the task is to control direction, then the direction instrument should provide information in terms of direction of flight and rate and direction of turning. Contrast this with the practice of indirect presentation, characteristic of our contemporary instrumentation, in which instruments frequently supply information not needed for its own sake but used indirectly to infer the desired information.

## THE COORDINATION OF CONTROLS

Up to now we have considered the control of altitude and direction as being achieved independently of each other. This, of course, is not the case, because one is dependent upon the other. As a result, further difficulties of manipulation are encountered. Once again the fault lies with the controls. For example, with conventional controls, if a turn is made, altitude is also affected unless the pilot takes the precaution of compensating for the loss of vertical lift during the turn. This means that he must manipulate his altitude indicator at the same time he is trying to manipulate his turn indicator. But, if the pilot had a turn control that caused the plane to turn without at the same time affecting altitude, the task would be greatly simplified. Sometimes the pilot wishes to change altitude and direction simultaneously as in climbing or gliding turns. To do this he must manipulate two or more indicators with two interdependent controls.

It might be expected that, because the artificial horizon combines both altitude and direction information in the same instrument, performance using it would be superior to performance using separate instruments for each. Such is not the case, however, in the Link. The combination is most probably an advantage, but as before, the horizon fails because it does not tell the pilot how much pitch and how much bank is required to make good the performance desired. As a result, the pilot must look away from the horizon and check with other instruments to determine by trial and error what attitude is correct for his purposes. If, on the other hand, the artificial horizon could somehow present all the needed information, then we would expect that performance using it would be superior to that now obtained.

There is one more point to be considered before integrating all this material. Because altitude is actually manipulated by two independent controls, the process of integrating their use is always a problem. This is very obviously a control problem because if a plane could be designed with one CLIMB-DESCEND lever, the difficulty would cease to exist. This is not impossible to do; in fact, it is being done now in an experimental Ercoupe. Nevertheless, postulating conventional controls, what can be done to simplify the problem?

In actual practice, controlling altitude is a two-stage process. The throttle is set to give the approximate altitude performance desired, then fine adjustments are made using the elevator (or trim). To know how to use the elevator, the pilot must receive cues from the airspeed indicator, the altimeter, the rate of climb, and the artificial horizon, none of which, as we have seen, tells exactly what he needs to know in a way that makes this information easy to use. Improvement, therefore, must come in these instruments in the manner previously outlined. Throttle control can also be improved. Power is shown in terms of r.p.m. and manifold pressure, and these instruments are calibrated numerically. However, the pilot is not interested in the numbers themselves only in what they represent. Calibration in terms of takeoff, climb, cruise, and so forth would, therefore, seem to be indicated.

## CONCLUSIONS

To sum up from a slightly different point of view, we have concluded from the evidence available that the difficulties of manipulating altitude and direction arise because the controls used for manipulation are not suited to their purposes. There are no unique altitude or direction controls. Instead, the relationships between control movements and altitude or direction performance are devious and variable, changing with thrust, airspeed, and attitude. These relationships are also nonlinear. Instruments that directly reflect performance are, therefore, basically difficult to manipulate with conventional controls.

The difficulty is intensified by the design of the instruments themselves. Current instruments do not meet the first requirement; their pointers or indicators do not respond appropriately to the control movements that activate them. A single exception in both the Link trainer and the airplane is the artificial horizon. Not only are its indicator movements appropriate, but the very thing it shows, that is, attitude, is more directly and closely related to the function of conventional controls than is any other aspect of flight performance. Nevertheless, the considerable advantage gained by this fact is lost because the instrument itself is not calibrated in terms of the subgoals the pilot is attempting to control. This failure, then, involves the second requirement, which, in the case of the artificial horizon, is not met. This is the criterion of pertinency of information.

Thus, in the present-day cockpit, some instruments meet the first requirement, others meet the second. But no instrument meets both. The instrument that comes closest to meeting both is the rate of climb indicator in the Link trainer. Here, because the Link does not simulate the inertia of an airplane with high fidelity, the rate of climb indicator gains an appropriateness of movement similar to the artificial horizon. As would be predicted, performance is superior in this case to performance obtained when using instruments meeting only one requirement. The problem now is to design instruments that will fulfill both requirements.

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# Suggestions Concerning Desirable Display Characteristics for Aircraft Instruments

INTERIM REPORT SDC 71-16-4, JULY 1949

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## CONTEXT

Display characteristics referred to in this report are those that determine the speed and accuracy with which aircraft instrument displays may be interpreted and used by pilots. They in no way refer to the engineering criteria that displays must meet. It is recognized that the best displays from the pilot's point of view are not always feasible because of cost, complexity, size, or weight. In the final selection of displays for use in aircraft, compromises must be made among these factors. In cases of compromise in which a choice exists between displays having different characteristics, the suggestions that follow are offered as a guide to selection.

## DISPLAY FUNCTIONS

In general, displays serve two functions in the cockpit. Either a display presents information that, by itself or in combination with other information, permits the pilot to arrive at one or more of the basic decisions he must make, or a display provides information that tells the pilot how to move the aircraft controls in order to execute one of his basic decisions. A single display may serve either or both of these functions, but the requirements for each are somewhat different.

To evaluate a display, it is helpful to know which function the display is intended to serve. If its purpose is to provide information the pilot requires in order to make a decision, this can be ascertained by asking whether the display helps tell the pilot what he ought to do in order to accomplish his flight mission. More specifically, does it tell the pilot in which direction he should fly, at which altitude he should fly, how far or long he should fly, or whether or not his aircraft is functioning properly in order to achieve his flight mission? If the purpose of the display is to tell the pilot how to move the controls, this can be recognized from the fact that such displays usually contain two indices, one representing the desired performance of the aircraft, the other representing its actual performance. One or both of these indices can be made to move as a result of manipulating the aircraft controls. The pilot's task is to align the two indices by positioning the moving index. The pilot both causes the index to move and uses his perception of its movement to guide subsequent manipulation of the controls. These are the instruments usually called flight instruments.

## SUMMARY OF DESIRABLE DISPLAY CHARACTERISTICS

The following suggestions are offered as guides for the selection of displays:

1. Choose a display that is legible; if a display is nonlegible in any respect, it should not be selected.
2. For displays that provide information necessary to make a decision:
   a. Choose the display that requires the least additional information from other sources in order to form a complete decision concerning direction, altitude, and distance for flight.
   b. Choose the display that best provides a common frame of reference for combining the various items of information it presents; the meaning of any one item of information with respect to any other should be immediately apparent.
   c. If the display does not present all the information that is necessary (and most displays do not), choose the display that provides a frame of reference within which the pilot can place and interpret additional information from other sources.
3. For displays that provide information used to guide control movements:
   a. Choose the display that has the moving index most easily positioned by manipulation of appropriate flight controls; this will be the display with the simplest transformation of control movement into index movement.

  b. Choose the display that requires the least use of additional displays in order for its indices to be aligned by the pilot.
  c. If displays contain more than one pair of indices, choose the display that best provides a common frame of reference for all pairs.

4. For both types of display:
   a. Choose the display that uses the moving index to represent the aircraft or aircraft performance.

For a detailed explanation of these suggestions, the reader is referred to the balance of this report which follows.

## WHY PSYCHOLOGISTS?

It may seem strange to the engineer that psychologists are interested in aircraft instruments. Explanations for such an interest usually begin with statements about the growing complexity of modern aircraft and how this complexity causes pilots to make errors under some circumstances. The need for simplification is emphasized. Although the need for simplification may exist, complexity as such is not the basic reason for the psychologist's interest. Even in the simplest of light aircraft there are problems facing the pilot that are psychological in nature and that are related to the design of the aircraft controls and the manner of presenting flight information to the pilot. Pilots make errors in Piper Cubs as well as in multi-engine aircraft, probably, in fact, more errors. The psychologist's interest in pilot errors is, therefore, not confined to errors in reading instruments or errors in handling switches, levers, and other nonflight controls. Instead, he is interested in any error that the pilot makes or in any difficulty in flying that the pilot may encounter. He knows that although the source of such errors may be traced to lack of training or poor training, their occurrence can also be ascribed to inadequate means for presenting the pilot with information or to providing him with controls that are difficult to use.

If a pilot overshoots a landing field or stalls out of a steep turn, we may be sure it was not done intentionally; the error occurred because the pilot failed to respond or responded in the wrong way to information that was present and could have been used properly. Lack of training may account for his failure in one sense, but, had the critical information been presented in an unmistakable manner, requiring little or no interpretation, and in a manner which demanded a proper response, the error could have been prevented.

In contact flying, because most critical information comes from the visual display of the ground and horizon, it is difficult to modify the way in which it is presented. But in instrument flying the opportunity for controlling the way in which information is presented to the pilot is greatly increased. Because almost all information comes to the pilot through man-made devices, a knowledge of the pilot's information requirements could conceivably suggest displays that would make instrument flying an easier task than contact flying.

Thus, the psychologist's interest in this field depends upon the fact that human beings constitute one element in the system of aircraft flight, one link in the chain, as it were. Other elements are, of course, the aircraft itself, the aircraft instruments, ground facilities, and established air traffic procedures. He knows that pilots make errors and otherwise perform inefficiently at times, and he knows that the frequency of this undesirable behavior can be materially reduced through attention to the design of the instrument displays and controls the pilot works with. When the pilot does act inefficiently, all the precision built into the rest of the system, the precision of radio navigation aids and instruments, is lost insofar as the end product, the flight itself, is concerned.

The psychologist knows that greater and greater precision built into the machine components of the system will not necessarily yield corresponding increases in precision for the system as a whole. Whenever the errors made by man overshadow the errors inherent in the machine, the reduction of man errors has a greater effect than the reduction of machine errors. Variable errors from independent sources are added in a system according to the square root of the sum of their squares. Thus, if a machine contributes an error of 4 units, and the man using the machine an error of 10 units, then the average error of the man-machine combination will not be $4 + 10$, or 14 units, but will be $\sqrt{4^2 + 10^2}$ or 10.770 units. If the machine error were cut in half, that is, reduced by 2 units, these 2 units would not be saved in the error of the combination. Instead, the combination error would be $\sqrt{2^2 + 10^2} = 10.198$, or a saving of only .572 units. As the ratio between the larger and smaller errors increases, the saving accomplished by reducing the smaller error becomes relatively less. The point should not be overlooked that a sacrifice in the precision of the machine could result in an increase in the efficiency of the whole system if, by making the sacrifice, the man were enabled to work more precisely.

If it is true that the reduction of pilot error is a desirable objective, and if such a reduction can be achieved, in part, through the design of instrument displays and controls, then what characteristics of design are important in this respect? To get an answer to this question, it is fruitful to look at the problem from a somewhat different point of view. The pilot as a unit in the flight system has specific tasks to perform. His tasks are primarily those of communication and control. The pilot, by virtue of being a human being, also possesses certain unique characteristics that determine the way in which he will perform these tasks. As part of a system, the pilot does not perform in isolation. In the system, his function is to receive a continuous stream of inputs in the form of signals, messages, reports, instrument indications, control pressures, and other stimuli, to organize these inputs, combine them, interpret them, compare them with stored inputs from memory, and, finally, to transform them into a series of outputs in the form of aircraft control movements and other motor acts. Because the pilot possesses his own unique characteristics as a functional element in the system, these impose certain requirements that determine what inputs are necessary for the task at hand and what form they must be in to be acceptable. His characteristics likewise impose restrictions on the type of output the pilot can generate.

As a functioning mechanism in the system, the pilot will accept a wide range of inputs in a variety of forms. In this respect, he is versatile compared to the mechanical or electrical components of the system. Furthermore, his tolerance to variations in input as well as his outputs can be modified by training. Although in many respects this is fortunate, it has also become a handicap. The pilot does not function with uniform efficiency over the range of inputs he will accept. Yet, because he will accept a wide range, the tendency has been to present him with just any input that happens to be convenient from other points of view. But for maximum efficiency there are optimum inputs, and these, in turn, depend upon the particular task in question. If optimum inputs can be specified, then ways of providing the pilot with such inputs can be devised through the design of instrument displays and other media for the transmission of information.

## COMPUTER AND SERVO

In setting out to discover optimum inputs, we have found it useful to divide the pilot's task into two functions: in part of his task, he acts as a computer; in the other part, he acts as a servo. This division between discrimination and manipulation functions was postulated as a result of an analysis of what the pilot does when flying an airplane. Among many other duties, it seemed evident that the pilot was continuously engaged in aligning two indices, one index representing the desired performance of the aircraft, the other representing the actual performance of the aircraft. These indices are represented by such things as dial markings and dial pointers, the axes of the airplane and the horizon, various radio signals, and instrument needles and reference marks. Alignment of these indices constitutes the pilot's most persistent task.

Close analysis of the alignment task shows that either the index representing the desired performance of the aircraft or the index representing actual performance can be made to move as a result of manipulating the aircraft controls. Furthermore, in any given alignment task, the pilot is always presented with a choice of many indices. For example, in using a compass, there are 360 points or indices on the compass rose (representing desired performance) which could be aligned with the lubber line (representing actual performance); in the case of the altimeter, the needle (representing actual performance) could be aligned with any one of many indices on the dial (representing desired performance). Such numerosity of possible indices of desired performance is characteristic of almost all alignment tasks including those involving contact flight.

In all cases, it is necessary for the pilot to choose the proper index for alignment. He must always answer the questions:

"Which heading should I take?"
"At what altitude should I fly?"
"How far or long should I fly?"

His answers to these questions are manifested in the selection of some one index from among the many displayed by the instruments in question. All pilot activity involved in selecting an index may be classified as discrimination, decision, or choice behavior. On the other hand, once the index has been selected, the pilot must bring about an alignment between it and its mate by moving the controls. This activity may be classified as manipulation or performance behavior.

Discrimination behavior is analogous to the function of a computer; manipulation behavior resembles the performance of a servo. Psychologically, these two kinds of behavior are in many ways independent. Whereas manipulation is primarily a motor skill, discrimination is a mental ability. The precision with which an alignment is brought about does not depend upon the correctness of the choice of indices to be aligned. Likewise, a correct choice of indices does not assure an adequate alignment. Pilots will see in these categories reflections of the familiar descriptions of judgment versus technique which appear everywhere in flight training.

Dividing the pilot's task in this manner is useful because optimum inputs for discrimination behavior are quite different in nature from optimum inputs for manipulation behavior. Since the inputs for both kinds of behavior come from displays, and since a single display may be made to serve both functions, it is useful to keep in mind the separate requirements of each so that they will not become mixed up. In order to provide a background for discussing these requirements, the following sections will be devoted to more detailed descriptions of discrimination and manipulation.

### More about Discrimination

When the pilot engages in discrimination behavior, what he does is to seek out and accept many different kinds of information. These he sorts and combines until he is left with just a few conclusions which represent, in appropriate proportions, all of the information originally taken in. The whole process can be thought of as a funnel. Into the wide end goes a variety of information; out of the narrow end comes a single representative conclusion. Actually there are three such outlets: one for conclusions concerning the direction for flight, a second concerned with altitude for flight, and a third for distance or time for flight. These are the basic decisions or choices a pilot must make because they represent the dimensions of space in which the aircraft is free to move. There is also a fourth outlet for conclusions of a somewhat different kind concerning the mechanical operation of the aircraft.

The information going into the funnel consists of such things as position information, geographic and terrain information, weather information, traffic information, information about the performance limitations of the aircraft, and information about ground installations including signals from radio navigation aids. The pilot also has a knowledge of the mission or purpose of his flight. This he uses as an integrating principle and as a criterion for establishing the validity of his decisions.

To compound the simile, we may think of this funnel as an apparatus for digestion. It needs certain staple foods to function at all. Although it is widely tolerant of how they are cooked and served, it definitely has preferences in these respects and will reward their observance with optimum output. But above all, it is lazy and will respond best when its foods are predigested.

In writing specifications for a display, it is possible to determine to what extent it belongs to the discrimination process by asking some questions about the purpose of the instrument. Does the display tell the pilot which way to fly, how far or long to fly, or at what altitude to fly in order to achieve his flight mission? If it does perform one of these functions, does it do so completely without requiring additional information from any other source? Does it provide information which, when combined with other information, will result in decisions concerning direction, altitude, and distance? If a display provides information of this nature, it belongs to the discrimination process (it may also provide manipulation information), and its function in this respect is to help select an index of desired performance.

### More about Manipulation

The act of aligning an index of desired performance and an index of actual performance is called manipulation. The alignment is brought about by moving the aircraft controls. Movement of the appropriate controls causes one or the other index (or both) to move, and in this way it can be aligned with its mate. Evidently the ease with which an alignment can be made depends upon the precision with which the moving index or indices can be positioned. This in turn depends upon the relationships between the movements of the controls and the movements of the indices. These relationships vary widely, depending on what the moving indices represent and which controls are used to move them. In addition, the alignment of one set of indices often affects the alignment of other sets so that the pilot must monitor several sets simultaneously. Likewise, some indices can be moved by several different controls which requires coordination of alternate control movements. The pilot's manipulation task is complex. There is no better evidence of this than the length of time it takes to learn how to fly and the necessity for constant practice to maintain proficiency.

The task of aligning indices is analogous in function to a closed servo loop. The pilot observes a discrepancy between the two indices to be aligned. He attempts to reduce this discrepancy to zero by moving the controls. Movement of the controls causes the aircraft to change its performance. This change is in turn reflected by movement of a display index. The movement of the display index is observed by the pilot, and what he sees then governs his subsequent control movements. Thus the loop is complete.

In the discussion of discrimination, we emphasized that, aside from the assessment of the aircraft's moment-to-moment mechanical operation, the three ultimate decisions a pilot must make concern direction, distance, and altitude, representing the spatial dimensions in which the aircraft moves. If this is the case, then it would seem that the pilot should need only three sets of indices to align, one for direction, one for altitude, and one for distance. But we know that if a pilot were given only a compass, an altimeter, and distance-measuring equipment, and nothing else (no contact vision either), he would not do a very good job even though the index of desired performance were specified in each case. Why not?

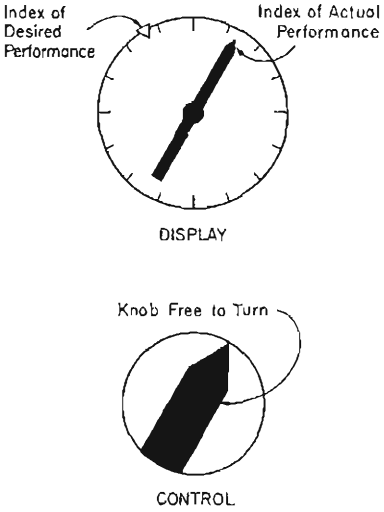


**Exhibit 1. Example of a simple, direct, one-to-one, control-display relationship well suited to human capabilities.**

The reason why not is a problem in manipulation. The answer lies in the relationship between the movement of the controls and the movement of the direction, altitude, and distance indices. One example should make this clear. Suppose the pilot had a direction control and direction display as shown in Exhibit 1. Suppose that the index needle on the display moved exactly according to the movement of the control knob. If the control knob were turned to the right through 90 degrees, the needle would follow exactly the movement of the knob with the same acceleration, rate, and displacement. Under these circumstances, direction control would be simple to perform. The movement relationship between control and index is direct and uncomplex and well suited to human capabilities. By observing the movement of the display index, the pilot is perfectly informed concerning how to move the control.

Actually, of course, the airplane does not fly in a way that would permit a movement relationship of that sort. And the direction controls, aileron plus rudder and elevator, do not bear the same kind of relationship to the compass as is the case in the illustration. A displacement of aileron does not result in a corresponding displacement of the compass needle. Instead, aileron displacement results roughly in an acceleration of the compass needle. This in itself is a difficult movement relationship for a human to utilize. In addition, there is a slight time lag involved, which causes the index movement to feed back to the pilot information that is slightly out of date. Finally, there are tendencies for index movements not directly caused by the control movement itself to enter into the system. These come from the overbanking tendency, rough air, negative yaw, and several other factors, all of which produce movement relationships between the various controls and the heading index that are difficult for a human to utilize with precision. Observing how the compass needle moves does not perfectly inform the pilot how to move the aileron, rudder, and elevator.

The point to be made here is that regardless of what factors may cause a given control-index movement relationship, the pilot is obliged to cope with it since he depends upon the movement of the index to govern his movement of the control. In the case of direction, altitude, and distance, the primary indices are difficult to position. To help him out, additional indices are provided in separate instruments. Alignment of these indices helps him govern the acceleration and rate of movement of the original direction, altitude, or distance indices while they are being positioned. Thus, the rate of turn, angles of bank and pitch, rate of climb, and airspeed indicators are found in the cockpit. All of these are added to help inform the pilot how to move his controls because the original, or primary, indices in which he is most interested are not adequate in this respect.

In designing instruments for manipulation, the engineer should consider the movement relationships between the indices of his instruments and the controls that activate them. He should ask himself such questions as:

> Can the movement of the index be controlled directly and with precision, or are additional indices needed to help guide control movements?
>
> Could the controls be modified (as with an automatic pilot, for example) to make positioning of the index an easier task?

Could the desired performance in question be represented by another kind of index with better movement relationships?

## SUGGESTIONS FOR OPTIMUM INPUTS

At this point we will attempt to make suggestions concerning inputs for discrimination and manipulation behavior. The suggestions are based on what has been found to be the case in many experiments from many laboratories. Although the suggestions are based upon experiments, the supporting data are not conclusive in all instances. Where the data are meager, we have filled in with imagination, or perhaps it would be better to say with educated guesses.

### Legibility

The first suggestion is that no display can provide an optimum input unless it is legible. Whether the display involves vision or some other sense modality, it must be clearly perceptible and distinguishable. Some of the factors governing the legibility of a visual display are size, illumination, contrast (both color and brightness), and form. With auditory displays, relevant factors include signal to noise ratio, intensity, pitch, duration, and distortion. The specifications for a display should be checked to be sure that adequate legibility will be obtained.

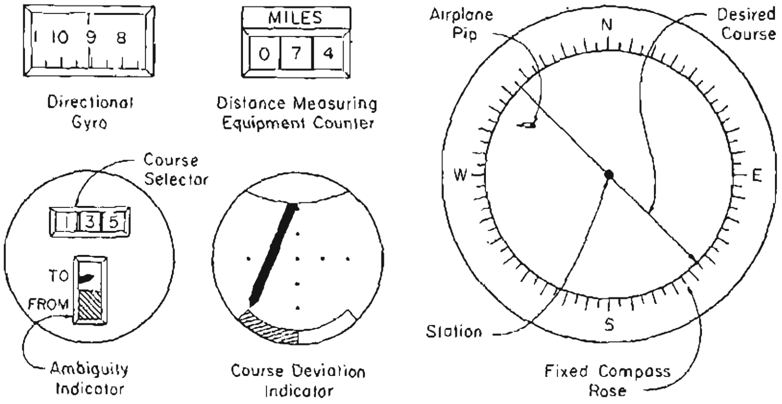
### Predigestion

The second suggestion is that displays that provide inputs for discrimination should predigest the information they present as much as possible. Displays should require a minimum of interpretation to use. The question is, how can this be brought about?

Information must be presented within some frame of reference. This frame of reference may be a system of polar coordinates or rectangular coordinates; it may be a number system or a tonal system or a system of colors or perhaps a time system. There are many frames of reference. What the frame of reference does is to connect or relate all the things that fall within it. For example, if I should select the number 10 as an item of information, then having gone to school and knowing all about numbers, you immediately know the relationship between 10 and a great many other numbers. You know that 10 is four times smaller than 40 and that it is twice as big as five. You know that it is three less than 13 and that multiplied by itself it gives 100. You may even know that the square root of 10 is 3.162.

Thus, because the number 10 occurs in a familiar system and you know the rules for getting around in the system, you can establish the relationship between 10 and the other numbers within the system.

We have seen that discrimination behavior involves combining information from many different sources. Different items of information cannot be combined if they occur in separate frames of reference. On the other hand, if they are presented in a common frame of reference, they can be combined, provided the person doing the combining knows the rules for getting around within the system. You cannot, for example, decide which way to fly if your position is specified in terms of bearing and range from a given point (one frame of reference) and your destination is given in terms of latitude and longitude (another frame of reference). A solution can be reached when a connection between the two frames of reference is established so that the information from one can be expressed in terms of the other. Thus, when the pilot has to combine information about the weather, the terrain, traffic control procedures, and the geography of his flight in order to decide on a direction for flying, this information must be reduced to a common frame of reference before a combination can be made. There seem to be two ways in which this can be accomplished. Either the pilot himself can bridge the gap between the various frames of reference involved, or else the displays can provide a common frame of reference in which the different items of information are or could be presented. An example of each is shown below.



DISPLAY A

DISPLAY B

Exhibit 2. Separated versus integrated, or predigested, presentations of position, course, and heading.

Exhibit 2 shows two displays for presenting various items of navigation information to the pilot. Display A presents each item of information separately to be combined by the pilot; Display B presents the same information all within a common frame of reference, which in this case is the face of the display itself. Display A has a VOR course selector, a TO-FROM ambiguity indicator, a course deviation indicator, a directional gyro, and a DME distance indicator. The information from each of these must be combined with the information from the others in order to decide which way to fly. These separate items of information belong in different but relatable frames of reference. The frame of reference in each case is a bearing and range system. But one system has its origin at the VOR station, and the other has its origin at the aircraft. The task of translating information from one system to the other is left to the pilot.

In Display B, the two bearing and range systems have been included within a common third system. The third system is simply the spatial continuum of the face of the display itself. All points and directions on this continuum are related, and their relationships are immediately apparent. Thus, positions with respect to one origin are also displayed with respect to the other origin.

To see how this works out, let us assume a theoretical problem. Suppose that traffic control requires an approach to the station from the northwest from a point 70 miles out. This information is specified in terms of the station-centered frame of reference. In the case of both displays, available information must be made meaningful in terms of the aircraft frame of reference so that the pilot will know which way to turn and what heading to turn to. In the case of Display A, this transformation involves either some complicated trigonometry, a special computer, or a very vivid imagination. In the case of Display B, the transformation has already been accomplished because all points specified in terms of the station are likewise displayed in relation to the aircraft and vice versa.

These displays were tried out with trained instrument pilots. It was found that the pilots made nearly five times as many errors when using Display A as when using Display B and that it took them nearly four times as long to use Display A (Roscoe, Smith, Johnson, Dittman, and Williams, 1950).

The first rule, then, for predigesting information by the design of a display is to see to it that the display provides a method for connecting the various frames of reference in which separate items of information appear. The designer of a display should determine first whether the display in question provides all the information needed to arrive at a decision. If it does not, he should determine what additional information will be needed and how it will be presented. Then he can decide how many frames of reference are involved and how these are related for the purposes of translation between them. His next step should be to try to eliminate as many of these as possible either by including them within an overall common frame of reference (as in the graphic Display B above) or by combining separate information items, the single product of which can then be presented as the only item of information the pilot needs to know. This latter method eliminates the need for combining items of information since only one item, the final product, is presented.

The second rule is that if the method of a common frame of reference is used, the one selected should be very familiar to the pilot. The frame of reference used in Display B was the face of the instrument itself. The face constitutes a restricted plane surface in which all the familiar rules for getting around apply, such as: a straight line is the shortest distance between two points, and parallel lines never intersect. The pilot is already familiar with a space such as this. He already knows and understands the system by which all its points and directions are related. He knows how to get around in such a space. Hence, when it is used to represent the navigation problem he is faced with, the well-known rules for getting around within the space also serve to get him around with respect to the problem, and the solution becomes an easy one.

If, on the other hand, the rules for the space did not happen to fit the rules for the problem, then the solution would not be easy. Suppose that a Mercator projection covering a large area of the world were presented on the face of the display. The display would not be as easy to use as a Lambert conformal projection, for example. In the Mercator projection, the shortest distance between points is not always a straight line. Parallel lines may appear to diverge, and the distance scale is not uniform throughout. Thus, the familiar frame of reference would be of no use to the pilot. He would have to learn the unfamiliar system of a Mercator projection in order to interpret the display.

### The Moving Part

The third suggestion is that the part of a display that moves should represent the aircraft. The moving part should be the index of actual performance rather than the index of desired performance.

The needle should be flown to the instrument rather than flying the instrument to the needle. On a graphic navigation display, the aircraft should be shown moving with respect to the ground rather than the ground shown moving with respect to the aircraft.

There is experimental evidence to support this contention. In contact flight, whenever the ground appears to move rather than the aircraft, the pilot is very close to vertigo. This often happens with new pilots in spins and other aerobatics. Any pilot, while flying, is firmly convinced of his own movement and orients himself accordingly.

Experiments have been performed to study the direction of motion issue. Two graphic VOR navigation displays were studied (Payne, 1952). They were alike, except that, in one case, the VOR station was fixed at the center of the instrument and the aircraft could move according to its position with respect to the station; in the other display, the aircraft was fixed at the center, and the VOR station could move according to its position with respect to the aircraft. The former display was superior to the latter in terms of the number of errors made while using it and in terms of the time required for interpretation. Some insight into the reason for this difference between displays was obtained by asking the pilots to predict the movement of the aircraft, in one case, and the station, in the other case, if certain patterns were to be flown. The difference here was unmistakable. Although the movements of the aircraft could always be predicted quickly and accurately, the movements of the station were very difficult to predict, and mistakes were made even after considerable practice at the task. In order to solve problems successfully using the aircraft-centered display, pilots would have to regard the display as if the station rather than the aircraft were fixed, calculate what movements the airplane would make, and then reinterpret these in terms of how the station would appear to move with respect to the aircraft.

In the case of needle and pointer instruments, other findings reported by Fitts and Jones (1947) tend to show that the pilot associates himself with the moving part of the instrument and that, therefore, it is preferable to have the moving part represent his aircraft. In all cases, evidence now available indicates that the moving part should represent the aircraft.

### Index-Control Movement Relationship

The fourth and last suggestion is that attention should be paid to the movement relationship between the display index and the aircraft controls that activate it. An optimum relationship should be sought. The ease with which pilots can align indices seems to depend upon the precision with which the moving index can be positioned. This in turn depends upon several factors governing the relation between the aircraft control movements and the movements of the indices. Some of the more important factors are:

1. The basic kind of index-control relationship
2. Time lag
3. Sensitivity
4. Extraneous factors

By the kind of index-control relationship we mean whether a displacement of the control results in a corresponding displacement of the index, a rate of movement of the index, an acceleration of the index, or some further derivative. Because the relationships are not always linear, are further obscured by interaction with other control movements, and depend upon the flight characteristics of the aircraft itself, the various kinds of relationships seldom appear in pure form. The implied classification, therefore, depends upon the basic tendency of the index to follow the control movement in a manner according to one of these categories. Tentatively, we know from tracking studies performed on human subjects and from observation of flying that a human performs best with a displacement or rate relationship. An acceleration relationship is more difficult for him to control, and a third derivative relationship is even more difficult.

In flying with present-day instrumentation, the pilot is called on to handle index-control movements corresponding to all these types. When an acceleration or even a further derivative relationship is involved, it has been found necessary to provide the pilot with additional indices representing the displacement or rate function of the performance in question. Otherwise, the pilot cannot position the original index, and his flying may actually become dangerous. Thus the localizer needle of the crosspointer instrument, the movement of which represents fundamentally the third integration of aileron-rudder displacement, is very difficult for the pilot to position when no other supplementary information is provided. But with sets of indices for heading and rate of turn (or angle of bank), positioning of the localizer needle becomes possible although it is still rather difficult to do precisely. Heading bears roughly an acceleration relationship with aileron displacement. So, to control heading, it has been found advisable to provide the pilot with pairs of indices for rate of turn or angle of bank.

A good rule to follow, then, in designing a display, is to determine the kind of fundamental relationship that exists between the moving index and the control that moves it. If the relationship is more than a displacement or rate relationship, then pairs of matchable indices should be provided for all intermediate derivatives. This rule may seem to be beside the point because the requisite indices are already present in most cockpits. They are present, but each is displayed by a separate instrument. Thus, in positioning the localizer needle, the pilot must also attend to positioning two other pairs of indices in two separate instruments—the directional gyro and the rate of turn indicator or angle of bank indicator. In addition to this performance, he also has to control altitude with various separate indices. He must listen to the radio. And so it goes. What the pilot sees happening to the localizer needle determines what indices he wants to match in the directional gyro. This, in turn, determines what he wants to match in the rate of turn indicator. At the same time, an error in alignment at any point in the chain necessitates new alignment requirements at other points.

The whole process has a tendency to be unstable. This is shown by the pilot's inability to fly an asymptotic approach to the localizer beam. Instead, his flight path oscillates about the beam. These oscillations tend to damp out under most circumstances. But if the aircraft is close to the station where the beam is narrow, the speed with which cross-interpretations must be made from instrument to instrument is sometimes greater than the pilot can achieve and respond to. If that happens, the oscillations increase in amplitude, and performance breaks down.

The basic difficulty here seems to be tied up with the fact that separate instruments are used to present the necessary information. This in turn is a problem in frames of reference—the same sort of thing that we discussed above. Each instrument has its own separate frame of reference. In the case of manipulation instruments, the frame of reference is the area of the display against which the index moves. When separate instruments are involved, the relationships among the movements of the several indices are not readily apparent because each movement occurs in a different place against a different background. Movements, although related functionally, are not related perceptually. Thus, control becomes difficult.

When the indices are placed within a common frame of reference, when they are made to move in relation to each other within a common space continuum, then performance improves significantly. The design for one such display was suggested by Walter Grether at the Aero Medical Laboratory of the United States Air Force. This display is shown in Exhibit 3. Here the localizer needle and the heading index move with respect to a common frame of reference. It is simply necessary to align the heading index with the tip of the localizer needle to achieve an asymptotic approach to the localizer beam. Because this instrument does not provide indices for rate of turn or angle of bank, positioning the heading index is not as easy as it might be. Nevertheless, it appears to be a great improvement over the usual practice of presenting localizer and heading in separate instruments.

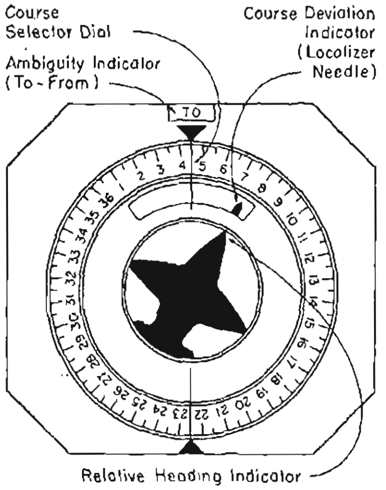


Exhibit 3. An example of the presentation of related indices of desired and actual performance within a common frame of reference.

A second and very familiar example of a common frame of reference occurs in contact flight. A task analogous to flying the localizer beam is the task of lining up with the runway on final approach. It is a task performed with greater ease and precision than flying the localizer beam. We suggest that a reason for this is that the relationships among position with respect to the runway, heading of the aircraft, and angle of bank of the aircraft are immediately perceptible to the pilot. All can be seen operating within a common frame of reference, and the relation between each index and the others is, therefore, immediately apparent.

Instead of supplying a common frame of reference for all indices, an alternate way of improving performance is to eliminate all but the single most easily positioned index and then, by means of automatic computers, specify the sequence of positions this index should take in order to produce the desired aircraft performance. In flying the localizer beam, the index most easily positioned, of all those the pilot uses, is the index for angle of bank. This index represents the actual performance or actual angle of bank of the aircraft. If a second index were provided representing the desired angle of bank —that is the angle of bank which at any given moment would cause the aircraft to fly according to an ideal flight path with respect to the beam—then alignment between these two indices would accomplish the desired performance of the aircraft. Since the angle of bank index is easily positioned, this would not be a difficult alignment to make. This principle has been utilized by the Sperry Gyroscope Company in the Sperry Zero Reader which, from informal reports, is not a difficult instrument to manipulate.

Other factors governing the index-control movement relationship are time lag, sensitivity, and extraneous forces, such as rough air. Since very little is known about these factors from the point of view of their effect on human manipulation proficiency, not much can be said about them now. Thus far, it would appear that very short time lags, as occur in the gyro instruments, are desirable. Sensitivity appears to have definite optimums, but what these are cannot be specified. Related to sensitivity are the effects of all index movements not directly attributable to manipulation of the controls. These movements should probably be reduced to a minimum. Thus, rough air has less effect on the artificial horizon than it has on the rate of turn indicator. Consequently, in rough air, the horizon is more easily positioned than the rate of turn needle. The acceleration and damping of index movement resulting from the stability and control characteristics of the aircraft introduce a further problem. They greatly complicate the relationships between control movements and index movements. They introduce what appear to be nonlinear distortions and variable time lags. Whether these can be compensated for in the design of displays is a questionable point. The more likely solution is to modify the stability and control characteristics of the aircraft itself. But that is a subject outside the scope of this report.

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