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Technical Report: NAVTRADEVCEN 316-2

RELATIVE MOTION III:
SOME RELATIVE MOTION PROBLEMS IN AVIATION

U.S. NAVAL TRAINING DEVICE CENTER
PORT WASHINGTON, L.I., NEW YORK

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SOME RELATIVE MOTION PROBLEMS IN AVIATION

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Abstract

This study was conducted for the purpose of exploring relative motion problems in a variety of pilot and navigator tasks. Field studies surveyed methods used by pilots to fly intercepts; analyzed the guidance of air-to-ground missiles; and identified relative motion problems in attitude and navigation displays including the ANIP display. In addition, two experiments were carried out to determine "natural" responses to "inside-out" displays as a function of display size, and to determine how to eliminate "wrong" responses to roll information presented on such displays ("reversal errors").

The study confirmed the superiority of outside-in displays, made specific recommendations for the design of navigation and attitude displays for air- and spacecraft, and suggested ways of eliminating reversal errors. It also recommended procedures for missile guidance, and provided insights into the cues that pilots use in visual intercepts.

F O R E W O R D

Introduction

Understanding and applying the principles of relative motion has long been recognized as a training area of prime military importance and also as one presenting extremely difficult training problems. In the operation of any vehicle (or in the delivery of a weapon) relative motion problems must be solved in order to hit a target, avoid collision with obstacles or terrain, follow prescribed courses, or establish and maintain a position relative to other vehicles. The first study in this series (Runyon et al, 1958) served to define and develop hypotheses with regard to the resolution of relative motion situations. The second study (Kelley et al, 1959) involved a mathematical description of relative motion situations and experimentation in their perception. Techniques were developed for converting the description of motion in one frame of reference to valid descriptions in other frames of reference. The present report deals with field studies and laboratory experiments in aircraft and spacecraft applications. Despite the areas of application, the results are generalizable in large measure to the control of ships, submarines and land vehicles.

Vehicle operators (for convenience we will take the case of the pilot) are accustomed to visualize relative motion situations in two ways. In the "inside-out" the pilot sees the world as it appears from the cockpit. In the "outside-in" the pilot is removed from his plane and sees it moving in the real world. This distinction is important in the present study since aircraft attitude displays parallel these two modes of presentation.

Procedure

Three field studies were made. One involved an analysis of the methods used by interceptor pilots in air-to-air interception. In the second, manual guidance for an air-to-air missile situation was studied analytically, followed by a pilot study to verify hypotheses. In the third, analyses were made of the relative motion problems in vehicle attitude displays, in dynamic navigational displays and in the special problem of attitude displays in spacecraft. The analysis of vehicle displays led to a series of pilot studies of responses to displays in order to define the problem areas. As a result of these pilot studies, two experiments were structured. The first of these examined differences between response to pitch and response to roll motions in horizon type attitude displays. The second experiment explored the effect of system lags on elimination of reversal errors.

Results

1. The most significant result is the substantiation of previous human engineering research which overwhelmingly supports the outside-in configuration as superior. Observations were made on the ANIP contact analogue display, a sophisticated version of the inside-out type, and it was found that while pilots responded correctly, untrained subjects made frequent reversal errors in attitude control, especially in control of roll. A modification of the contact analogue

display is suggested to remedy this condition. An extension of these findings leads to a recommendation for a three axis outside-in display for use in spacecraft. The rationale here is that displays which take advantage of "natural" responses make for easier learning.

2. The analysis of air-to-ground missile guidance indicated that head or tail-on target courses which result in straight missile paths are most likely to score hits but that in any course the first few seconds of guidance are critical to the task. The need for training in this area and for a training device is indicated.

3. The advantages and disadvantages of four types of map display for navigation and maneuvering information are presented in terms of motion relationships, particularly with respect to possible conflict with other attitude displays in the cockpit. A north-oriented navigation display is recommended for complex maneuvers.

4. The experiment on reversal errors in control responses showed that errors are rapidly eliminated with a short lag system leading to a simple and effective training technique.

Implications

Through analysis and experimentation, the relative motion problems faced by vehicle operators have been explored both in the case where the real world is used and in the case where man-made displays are used for orientation. Valuable insights are provided in the problems of visual intercept, air-to-ground missile guidance, navigation and attitude control. Specific training recommendations are made in each of these areas, together with the spelling out of display modifications required to provide appropriate visual cues. The need for two specific training devices is spelled out, one for practise in the early phases of air-to-ground missile guidance, and the second for the elimination of reversal errors in attitude control.

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RECOMMENDATIONS

Training

1. Training in flying visual intercepts should include extensive practice in utilizing the important cues provided by shape, size, and changes in shape and size of the visual image of the other aircraft during the intercept. Motion picture training in these cues should be valuable. More valuable still would be an unprogrammed training device in which such cues were properly displayed.

2. Training in the use of grid lines, etched on windscreens to improve perception of relative motion of "bogeys," should be made an important aspect of training in visual interception.

3. Training for air-to-ground missile guidance should concentrate on the early phases of such guidance, and should teach the quick perception of the rate of change of errors. A training device by means of which extensive practice on the tracking responses required in the early phases of such guidance is important. Accurate simulation of the total task is unnecessary.

4. Any form of dynamic navigation display will result in special relative motion training problems. If the recommended north-oriented display is used, the problem is that the "own aircraft" symbol on the display is oriented differently than is the actual aircraft for headings other than north, and is exactly reversed flying south. Simulator training in flying with such a display is essential.

5. Training in control of roll so as to avoid reversal errors is important. Experienced pilots still make such reversals. A simple closed loop (unprogrammed) training device to "train out" reversal errors in roll should be developed. It should present sudden unpredictable roll disturbances to a subject. It should also have widely adjustable lag characteristics between control and display, so that training could begin with short lag systems and proceed to longer. This will effectively reduce reversal errors.

6. Contact analog type instruments, unless redesigned, will present essentially the same problem in training for the control of roll as do present artificial horizon instruments.

7. Contact analog type instruments or training devices could provide an excellent means of training for attitude control in contact flight, particularly for the control of roll.

8. Reversals in controlling pitch are less frequent than in controlling roll. Unlike response to roll, the natural response to pitch motion of a large articulated moving horizon-type display is appropriate. When the horizon display is small and schematic, the natural response is inappropriate, however, and training to prevent reversal errors is important, just as it is with roll.

Design

1. Interceptors should have uniform grid marks inscribed on their windscreens to help them perceive changes in relative position and size of "bogeys."

2. The most important single item of instrument information that might be supplied to an interceptor pilot is closing rate.

3. The dynamic navigation display design recommended for complex maneuvers is north-oriented, rather than heading-oriented.

4. The "inside-out" display concept is not recommended for indication of roll for any vehicle attitude indicator, including large integrated (contact analog) displays.

5. It is recommended that a modification in the contact analog concept such as shown in Figure 6, page 24, be considered.

Research

1. The relation between skill in performing visual intercepts, and use of relative rather than external frame of reference cues, should be measured quantitatively. If a high relation exists, training programs should then be oriented around teaching relative cues.

2. Experimentation should be initiated immediately on design of and training for utilizing dynamic navigation displays.

3. A training requirements study for three axis attitude control of manned space vehicles should be initiated.

4. A simulator to train out roll reversals (training recommendation 5) should be built, and its effectiveness adequately tested.

BRIEF OF THE STUDY

In the first phase (Runyon et al, 1958) of this series, the problem of relative motion was considered in a preliminary way. Several hypotheses were suggested for further study. These hypotheses centered about the possibly harmful effect of pilots attempting to perform maneuvers with respect to other moving vehicles from a non-relative "outside-in" view. The report suggested that training should perhaps stress the relative "inside-out" view in teaching such maneuvers, and the perceptual cues that produce this point of view.

The second phase of the series (Kelley et al, 1959) expanded the scope of the investigation. Relative motion was defined as change in the relative position of two objects, each of which is moving with respect to a reference framework defined by some third object. Various examples of relative motion situations were described, ranging from planetary motions to problems of maneuvering aircraft with respect to other moving aircraft, to problems occurring in connection with the use of moving indicators. Despite the frequent occurrance of such problems, a literature survey showed only a handful of studies directly concerned with relative motion. A much larger number proved to be indirectly related.

A mathematical description of relative motion problems, carried out in the second phase, presented techniques for converting the description of motion in one frame of reference to equally valid descriptions with respect to other frames of reference. It was shown how these techniques could be applied to the clarification of relative motion situations.

The second phase study consisted in large part in the analysis and systematization of the relative motion problem. Conclusions from this work include the following:

1. The relative motion problem hinges on the frame of reference to which one's own motions, and those of another moving object are referred. Possible frames of reference for vehicles maneuvering above the earth's surface include:

   a. Geographical (earth's crust)
   b. Air mass
   c. Other vehicle
   d. Own vehicle

Either of the last two can be called a "relative" frame of reference.

2. A relative reference frame should not be used:

   a. For long-range maneuvers, missions, navigation purposes, and similar extended operations.

   b. When good perceptual cues for a geographic frame of reference are available.

   c. When the operator has time to figure out or compute a correct maneuver with respect to a geographic or other large stable reference frame.

   d. When the relative frame of reference does not allow the operator to receive sufficient information to perform the maneuver correctly.

   e. When a good rule of thumb is available, which makes possible effective maneuvering without the necessity for adopting a relative motion reference frame.

3. Relative frames of reference are of potential value for certain important short-range maneuvers, where immediate response is required, where good geographic reference frame cues are missing, and where good rules of thumb for performing the required maneuvers have not been discovered.

4. The actual value of relative reference frames must be established by an experimental program, since neither the literature on the subject nor analysis of the problem is sufficient to assess their value.

The final stage of work reported in Phase II was an experiment which demonstrated that shape was a highly important cue in perceiving motion on the part of an aircraft having little in the way of background. The path of a sphere was perceived much less well than that of a model aircraft of the same size in this experiment.

The third phase, this present study, aimed to test relative motion hypotheses developed in Phase II of the project, and to spell out some of the implications of the research for operational and training equipment and procedures for military aviation tasks. Techniques used include both field observation and interviews, and laboratory experimentation. The organization of the project was as follows:

A. FIELD STUDIES

1. Air-to-air intercepts. Air-to-air intercepts were studied by semi-structured interview techniques, with seventeen Air Force interceptor pilots as subjects.

2. Air-to-ground missile guidance. Manual guidance of an air-to-ground missile was studied primarily analytically, but with information obtained by an analog computer pilot study of the problem in addition.

3. Relative motion problems in vehicle displays. Field studies of display problems included field surveys and analyses of the relative motion problems of: 1) vehicle attitude displays; 2) the special problem of attitude displays in spacecraft; and 3) dynamic navigation displays. These studies included observations of ANIP program displays for fixed and flexible wing aircraft, X-15 displays, and others.

B. LABORATORY STUDIES OF RELATIVE MOTION PROBLEMS IN DISPLAYS

1. Pilot studies. Five pilot studies of responses to displays by naive subjects and by pilots helped to define problem areas, and to structure the more extensive experiments.

2. Experiment 1: Response to pitch vs. response to roll. This, the major laboratory experiment of the project, demonstrated an important unsuspected difference between response to pitch and response to roll motions in a horizon-type attitude indicator.

3. Experiment 2: Effect of system lags on elimination of reversal errors. This experiment explored the effect of varying system lag on the number and duration of reversal errors in a simulated vehicular attitude control system.

The procedure followed was to first prepare complete descriptions of the two major divisions of project work, i.e., the field studies and the laboratory experimentation. These descriptions form Appendices to this report. This brief summarizes the work described in detail in the Appendices, and in its final section discusses implications of the study for training.

FIELD STUDIES

Air-to-Air Intercepts

Air-to-air intercepts were studied using semi-structured individual interviews and small discussion groups. Subjects were seventeen Air Force jet interceptor pilots stationed at Seymore Johnson and Shaw Air Force bases. The study sought to establish whether pilots used an "outside-in" geographic, or relative reference frame in flying intercepts, which visual cues were most important, how instrument information affects the intercept, and related information. Interview questions and answers are detailed in Appendix A.

Most of the pilots interviewed placed an emphasis on relative motion cues, with their own aircraft as the principal reference frame. Scratches, windscreen struts, gunsight reticles, and other similar cues were stressed. These provide the pilot with information about the position, attitude, and motion of the other aircraft with respect to his own aircraft. However, all pilots used non-relative cues to some extent, and a large minority relied on them heavily, describing background cues as more important than foreground. Unfortunately, there was no way to correlate the skill of pilots at performing intercepts with the tendency to rely on relative cues. According to the hypotheses of Runyon et al (1958) in the first report in this series on relative motion, such a correlation should be found, since these authors postulate that the growth of maneuvering skill depends on learning to rely on relative "inside-out" cues, instead of attempting to picture the maneuver in "outside-in" geographic terms. There was a tendency for the higher ranking of the officers interviewed to rely more on relative cues than the lower ranking officers, but this tendency was not sufficiently clear-cut to provide any real test of the hypothesis.

The frame of reference used in flying intercepts not only tended to vary among individuals, it also varied with the same individuals under different circumstances. Presence or absence of background cues was an important factor in determining whether or not an external reference frame could be utilized. Pilots differed in the extent to which they believed such cues important. The consensus was that a background such as a stratocumulous cloud layer was ideal, in that it provided both contrast and structure against which movement could be seen. Ground as opposed to cloud structure could be helpful at low but not high altitudes if contrast was adequate. Uniform featureless sky as background tended to be difficult.

Pilots unanimously agreed that shape and size and changes in shape and size of the image of other aircraft were extremely important in performing visual intercepts. This supports the experimental finding of the previous report in this series, and points to this cue as one which should be emphasized heavily in training.

The following additional points were made in the interviews:

1. Most, but not all pilots felt that instrument information per se was generally rather unimportant in perceiving the motion of the plane to be intercepted. Instruments mentioned as being important by some pilots were air speed, altitude, and heading, in that order.

2. It was agreed that speed changes by the other aircraft are the most difficult maneuver to correct for. Gradual changes in altitude and gradual changes in heading were also mentioned frequently.

3. If allowed to select what additional information they could best use in interception, rate of closure, target speed, target heading, and target range were mentioned in that order of frequency.

4. Individual pilots commented on the importance of experience in flying successful intercepts, the helpfulness of condensation trails, when present, and the need for a uniform grid drawn on the windscreen to show the relative motion and size of the target. This latter suggestion is of special interest, in view of comments by others on the importance of windscreen structure, scratches, and gunsight reticles.

Air-to-Ground Missile Guidance

Manually guided air-to-ground missiles pose special relative motion and relative motion training problems. The problem considered was limited to missiles guided to the target along a line of sight path from an aircraft flying a straight-line constant-speed course. Analysis of the problem showed that the simplest delivery in terms of missile relative motion occurred with head-on or tail-on target deliveries. All others required that the missile be flown along a path of ever changing curvature, and would be expected to result in misses if the pilot were interrupted during guidance. Head or tail-on target courses, on the other hand, resulted in straight missile paths which might well result in hits, even when guidance was interrupted.

A pilot study utilized an analog computer and large screen oscilloscope to simulate some important aspects of the air-to-ground missile guidance problem for offset deliveries involving curved courses. It was found that the initial phase of guidance was critically important for this task. When considerable deceleration of the missile occurred during flight, this was especially true, most failures occurring in consequence of the first few seconds of control. Training pilots to make quick and accurate initial control responses thus appears as the most important training requirement for this task.

Relative Motion Problems in Displays

Vehicle Attitude Display

The first and most important class of display considered in the field studies was the vehicle attitude display, and especially, the moving horizon-type attitude display. The latter is the cause of the motion problem that has received the most attention in the literature. The moving horizon display presents a relative motion problem because, while the horizon should form the stationary reference framework with respect to which the instrument panel and vehicle move, the horizon display is naturally perceived as moving with respect to the instrument panel.

The presentation of a frame of reference for vehicle motion within a display results in what has been termed an "inside-out" display. If instead a miniature moving aircraft were shown against a horizon that was fixed with respect to the instrument panel, as when painted onto a stationary part of the instrument, the display would be termed "outside-in." Human engineering research has overwhelmingly supported the "outside-in" configuration as superior. (Fitts, 1951) The previous report in this series (Kelley et al, 1959) pointed out that with a large articulated display, the content of the display might well form the frame of reference with respect to which the vehicle was perceived as moving. In such a case, the "inside-out" display configuration would be appropriate. It was thought that the ANIP contact analog type display, illustrated in Figure 1, fulfilled this condition. Observations failed to confirm this expectation. Simulators containing contact analog displays were flown and users interviewed. Although trained pilots respond correctly to the contact analog, untrained subjects make frequent reversal errors in attitude control, especially in control of roll. The display is

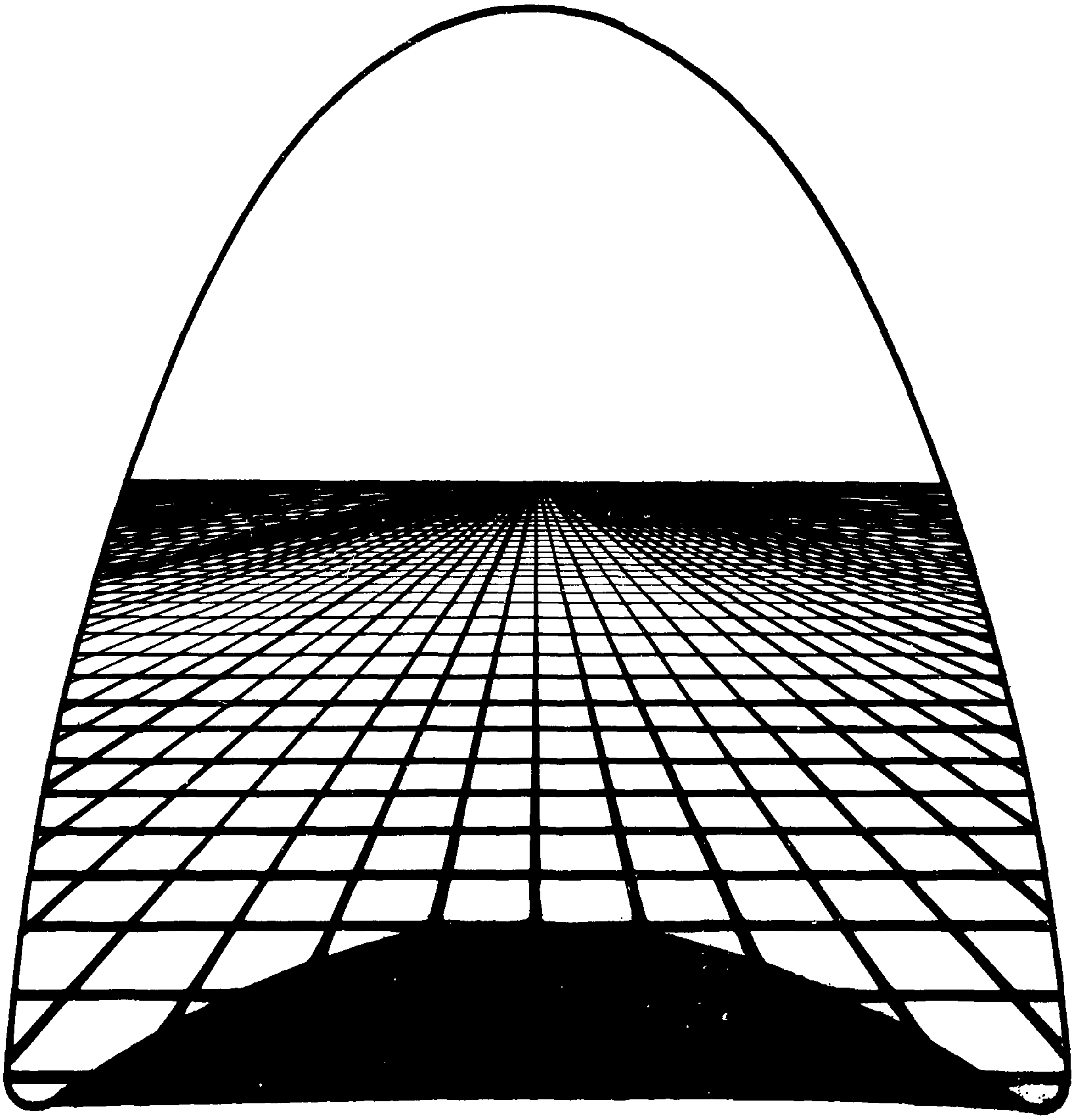

Figure 1. Sketch of an ANIP contact analog display.

apparently not sufficiently large or detailed to become the frame of reference for roll motion of the vehicle simulator. Conceivably, "large enough" might mean occupying substantially all of the visual field. In any case, one result of the field studies was to cast further doubt on the choice of "inside-out" attitude displays, even in the one situation where they had previously appeared justified; namely, the contact analog. A modification in the contact analog is suggested later in this report.

The Kinalog, developed by Fogel, is an artificial horizon indicator which, when an aircraft deviates from level flight in pitch or roll, first shows a moving aircraft ("outside-in") display that gradually changes to a moving horizon ("inside-out") configuration if the maneuver is sustained. It is claimed that the pilot's frame of reference changes in a similar fashion as a result of the influence of visual cues gradually giving way to that of vestibular. Further in-flight experimentation with the Kinalog is needed.

Attitude Displays in Spacecraft

A new application of information on vehicle attitude problems is the display of attitude in manned satellites and spacecraft. These displays may need to show three axes of attitude information. One such instrument is the Lear spherical indicator (Figure 2) which can display either two or three axes. The X-15 panel contains a Lear instrument. The moving sphere represents frame of reference information while stationary markings represent the vehicle, so this is an "inside-out" presentation. It is therefore likely to result in increased training time and increased probability of reversal errors for operators who are not pilots, and thus are not trained on the similar "inside-out" horizon indicator. It would appear feasible to convert the Lear instrument to an "outside-in" configuration, in which the vehicle were outlined on the moving sphere, and the frame of reference represented by stationary scale markings.

Figure 3 shows a three axis "outside-in" oscilloscope display used in the laboratory of Dunlap and Associates, Inc. The element moves up and down to show pitch, side to side to show yaw, and tilts to indicate roll. Experience has shown it to be an excellent display in terms of ease of learning, absence of reversal errors, and unity of the triplex presentation. A further improvement, consisting essentially of the addition of an ellipse showing three axis rate information by an ellipse with its origin on the center of the moving element, has been developed at the General Electric Missile and Space Vehicle Department by Mr. George Berbert of Dunlap and Associates, and Dr. Robert Knaff of General Electric. This display, which is described more fully in the Appendix,

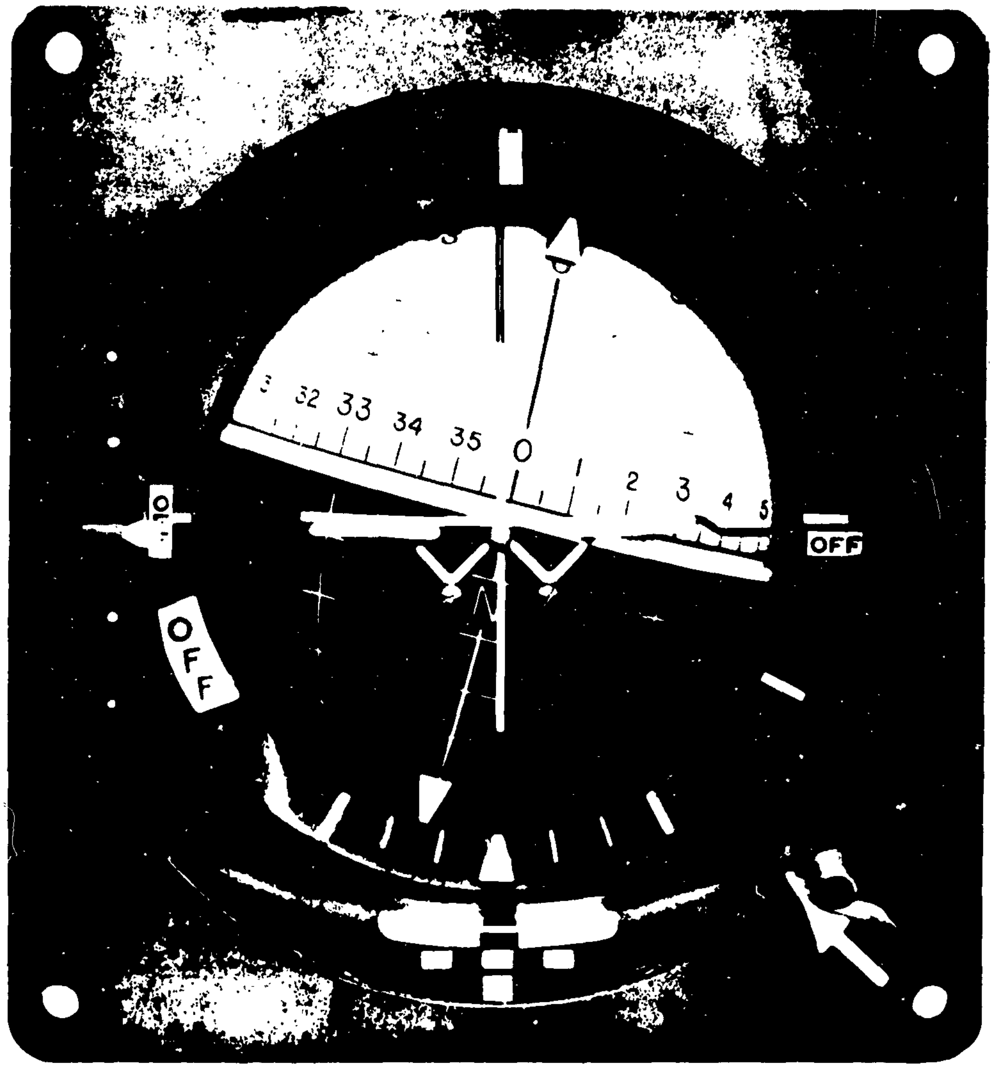

Figure 2. The Lear three axis flight attitude indicator. (Reproduced from: Lear Engineering Proposal No. 5061, March, 1958)

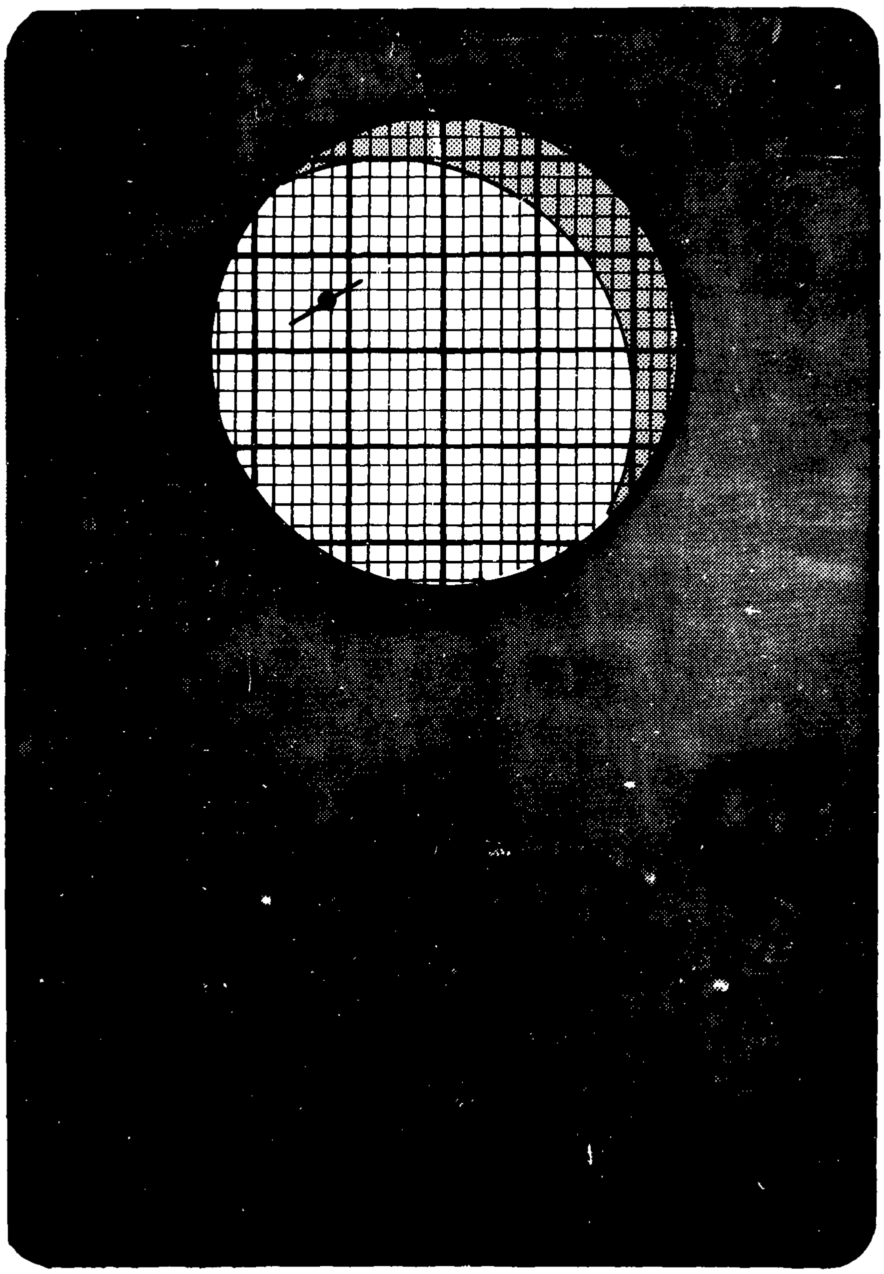

Figure 3. Three axis oscilloscope attitude display used in the laboratory of Dunlap and Associates, Inc.

is by far the most effective three axis attitude display the authors of this report have seen.

Dynamic Navigation Displays

The dynamic display of navigation and maneuvering information presents serious relative motion problems. Such displays are under development, however, and promise to play an important role in aviation in the future. The displays consist essentially of a map of some sort with symbols representing own and possibly other aircraft. Either the map or the aircraft symbols or both may move. There are four principal types of display in terms of motion relationships:

1. North-oriented, moving plane,
2. North-oriented, moving map,
3. Heading-oriented, moving plane, and
4. Heading-oriented, moving map.

The first of these is a completely "outside-in" display, the fourth completely "inside-out," while two and three are mixed types. All have disadvantages. The north-oriented display would confuse control-display and display-display relations on southerly courses, since in this case the "own aircraft" symbol would point in the opposite direction to the actual aircraft. The heading-oriented displays would, for southerly courses, show map printing and symbols upside down, and would, in addition, result in confusion of motion relationships when other moving aircraft were displayed. This is due to the fact that each change in heading would result in apparent motion of the other aircraft. A moving plane display has the disadvantage of having to jump to new map locations, while the moving map may not show motion relationships among moving aircraft clearly.

When complex maneuvers such as interception must be carried out with respect to other moving aircraft from one of these kinds of displays, the first or perhaps the second type of the four is recommended. The distortions in motion of other aircraft caused by heading changes in the third and fourth display is the principal factor governing this recommendation. When the true motions of other aircraft are less important to the pilot, as in straight navigation problems, the advantages of the fourth "inside-out" display weigh more heavily. The display coordinates best with what the pilot sees in contact flight, and with controls and other displays. The seriousness of the problem of reading a map upside down must be evaluated, however. To some it might be very objectionable.

A navigation display of the first type (north-oriented, moving map) which showed many aircraft maneuvering in a crowded airspace, was simulated in the laboratory of Dunlap and Associates, Inc., in connection with another research project. It is shown in Figure 4. The display was created by means of motion picture animation techniques. Observers felt the display was effective, and would prove easy to fly by.

LABORATORY EXPERIMENTS

Laboratory research, all of which concerned vehicle attitude displays, consisted of five small pilot studies and two larger experiments. These are described in detail in Appendix B, and summarized here. All utilized an aircraft joystick for vehicle attitude control, varying the pilot compartment and display as noted. The major items of equipment used throughout the program include the following:

1. Control stand. This consisted of pilot seat and aircraft joystick, connected to produce separate electrical signals when the stick was moved fore and aft or side to side.

2. Pilot compartment. This was a cloth-covered framework around the control stand to isolate the subject from the laboratory surroundings. The compartment and control stand could be tilted up to ten degrees in roll during simulated flight.

3. Display equipment. This included: a thirty-six inch diameter ground glass screen at panel distance from the subject, onto which slides and motion picture displays were back-projected; Kodachrome horizon slides, and motion picture horizon displays taken with a zoom lens to give the effect of forward motion towards the horizon; a five inch d. c. oscilloscope, placed at the base of the large display and tilted up toward the subject, on the face of which an artificial horizon display, electronically generated, could be presented; and a shadow-casting device by means of which a large "artificial horizon" consisting of a white semicircle over a black semicircle (Figure 5) could be cast on the ground glass screen.

Figure 4. Navigation display of type tested in the laboratory of Dunlap and Associates, Inc. Arrows represent aircraft, flying at velocity indicated by the arrow's length. (Very short arrows show helicopters.) The numbers show altitude in hundreds of feet. The circle on one arrow shows "own aircraft."

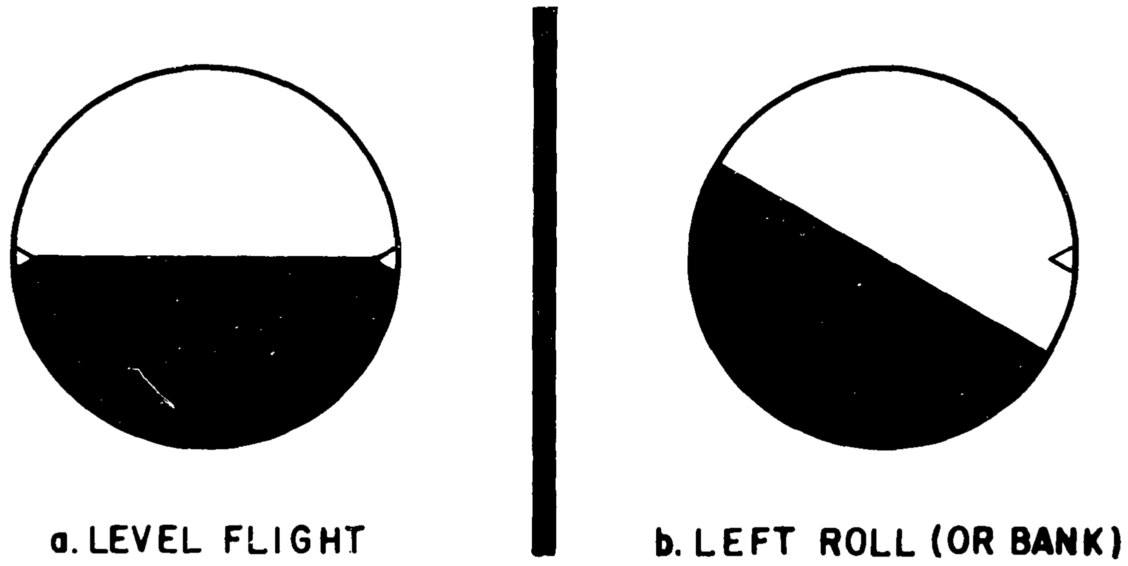

Figure 5. Schematic horizon display used in Pilot Study 1.

4. Computer. A fifteen amplifier Heathkit analog computer with standard accessories (multipliers, function generator) was used to generate the electronic display and to simulate the "vehicle" controlled in the final experiment, which involved closed loop (unprogrammed) attitude control.

5. Indicators and Recorders. Several voltmeters, a second oscilloscope, and a six channel recorder were employed for experimenters to monitor and, when desired, record experimental variables and subject responses.

Pilot Studies

The pilot studies began exploring the effect of display size and articulation on response to roll motion. In Pilot Study 1, the shadow-casting equipment was used to generate a large (thirty-six inch) roll display shown in Figure 5. The hypothesis tested was that this large horizon would become the frame of reference for motion, and in consequence, the response would be in the opposite direction to that naturally made for a small horizon display. Six subjects were tested, all of whom gave responses contrary to the hypothesis. It was decided to further test the hypothesis by a more realistic display.

Pilot Study 2 utilized a Kodachrome of the horizon and a 16 mm color motion picture of a horizon that realistically displayed the effect of forward motion in flight. The result was a beautifully articulated realistic display, larger than the view through many aircraft canopies. In addition, the pilot compartment was tilted small amounts irregularly. Despite this, only rarely did subjects respond as hypothesized. The natural response to roll motion on a display of any practical size was clearly "against" or "outside-in." The display content never became the frame of reference.

In Pilot Study 3, the same arrangement as Pilot Study 2 was used to compare the roll responses of five pilots and five non-pilots. It was presumed that pilots would respond with appropriate control movements, and non-pilots would continue, as in the first two studies, to respond inappropriately, i.e., in a way that would increase rather than decrease roll in a real aircraft. Three variations in type of roll movement were employed, so that errors in response to display position could be isolated from errors in response to display movement. Table 1 summarizes the results, which were in agreement with expectation. The number of errors by the pilot group was surprisingly high, however, and occurred primarily in response to display motion rather than display position. It appears that, despite flying experience, the tendency persists to move the control the wrong way while watching the moving horizon display of roll. The tendency to make an "outside-in" response to the display is much stronger than the experimenters had supposed, both for pilots and non-pilots.

Pilot Study 4 repeated Pilot Study 2 with the addition of goggles, which limited the subject's visual field to the display area, and in one eye only. This was to see if cutting out the surround would change the response of non-pilots to the large moving horizon display. It did not.

Pilot Study 5 repeated Pilot Study 4, but used pitch rather than roll motion of the large moving horizon display. Unlike responses to roll, the large preponderance of responses to pitch were appropriate or "inside-out," indicating that the display content had become the frame of reference with respect to which the vehicle moved. This interesting result called for fuller investigation, so Experiment 1 was conducted.

Table 1. Per cent of appropriate responses to banking of a horizon display by flyers as opposed to non-flyers.

Display Condition	5 Flyers	Subjects (4 most experienced) Flyers)	5 Non-Flyers
1. Started in bank which increased	80	(100)	12.5
2. Started level and banked	70	(88)	20
3. Started in bank which decreased	75	(94)	15

Experiment 1: Response to Pitch vs. Response to Roll

This experiment was to test the hypothesis that the natural control response of naive subjects to a large articulated moving horizon display is appropriate for pitch motions and inappropriate for roll, while the natural response to a small schematic moving horizon display is inappropriate for both pitch and roll. The Kodachrome horizon slide was used for the large display, the oscilloscope artificial horizon indicator for the small. Either display could be moved in pitch or in roll, and at comparable rates, so there were four display conditions. Trials with each condition included errors in display position only, in rate only, and in rate and position combined. After a subject was through, he was interviewed to see if he could correctly identify aircraft pitch and roll from the appearance of the display. Twenty-four male high school seniors comprised the experimental subjects. They were divided into eight groups of three, each of which received trials with the four displays in different sequence.

Statistical analysis showed that there were no detectable sequence effects, so data for all subjects was lumped. Differences among the kinds of trials (position vs. rate in the display) were small, so these were also combined.

The mean scores for each of the four display conditions over all trials with all subjects in per cent of appropriate ("inside-out") responses were:

large pitch display -- 65%
large roll display -- 17%
small pitch display -- 35%
small roll display -- 15%

Each percentage represents twelve trials for twenty-four subjects, or a total of 288 trials.

Differences between responses to the four display conditions taken by pairs were highly significant except for "large roll vs. small roll" which was insignificant.

The post-session interview to see if subjects could successfully associate display configuration with the correct direction of aircraft roll or pitch showed fifteen subjects correct on pitch, but only six correct on roll. Correctness or incorrectness on the interview was associated at a high level of significance with whether subjects made appropriate or inappropriate responses during the experiment.

In an addendum to this experiment, the response to yaw (side to side) motion on the large display was determined by three experimenters on each other. Yaw motion behaved like pitch motion, i.e., the natural response was "appropriate" or in the direction of the motion of the display (inside-out).

Experiment 1 confirms dramatically the hypothesis that roll and pitch motions bring about different responses on a large articulated display. Since yaw behaves like pitch in this respect, the appropriate generalization appears to be, "It is easier for display content to become the frame of reference for translational than for rotational motions of the display." This generalization is fully consistent with all data gathered in the experimental program.

Experiment 2: The Effect of Variations in System Lag on the Elimination of Reversal Errors in Vehicle Attitude Control

The most generally used aircraft attitude indicator, the small artificial horizon, is so designed that the naive subject will move a control inappropriately for both roll and pitch motions of the display. This poses a training problem. Experiment 2 is a training experiment. It tested the hypothesis that reversal errors are eliminated more quickly in training on a vehicular system having a short lag between control motion and vehicle response as shown on the attitude indicator than on a system having a long lag.

Three matched groups of four subjects each were selected on the basis of their responses in Experiment 1 to serve again as subjects in this experiment. Equipment was 1) the small oscilloscope display of roll; 2) analog computer simulations of vehicles having fast and slow roll responses to inputs from the control stick; 3) the control stand and pilot compartment used in previous experimentation; and 4) a six channel pen recorder. Roll, rate of change of roll, control stick position, a standardized sudden disturbance in roll occurring in randomized direction during each trial, a score showing how accurately the subject maintained control, and trial start and stop timing signals, were each recorded for each experimental trial.

The three groups of subjects were trained for five sets of ten trials each. Group one was trained on the short lag system, group two on the long, and group three on a mixture of the short and long lag systems. After the five training sessions, all subjects were tested with ten trials on the long lag system.

Table 2 shows the number and duration of initial reversal errors during training and test trials. Learning in the short lag group was so fast that by the end of the first training session initial reversals to the upset motion of the display were already rare. The other groups required a second training session to reach the same level. After the second training session reversals were rare, and no differences between the three groups were apparent. The very short reversals made in the fourth and fifth training sessions with the long lag group are of interest. They consisted of a clearcut motion in the wrong direction followed a reaction time later (.2 to .4 seconds) by a correct motion, long before any change could take place on the display.

In terms of accuracy of control, the mixed lag group performed significantly better than either of the other groups on the test condition. The short and long lag groups differed only slightly in this respect.

The experiment confirmed the hypothesis that reversal errors would be eliminated more quickly with short than with long lag systems, even though the control task was (apparently) "too easy," resulting in very few reversals after the earliest training sessions. The use of short lag systems in training to counteract the natural tendency toward reversal errors in use of the artificial horizon would be a simple training technique, and possibly quite useful.

Table 2: Number and mean duration in seconds of initial reversal errors of three groups of subjects trained on systems having different lag characteristics, during five training and one test trial.

	Training	Session					
Group	1	2	3	4	5	Test	Total
I. Short lag group							
Number of reversals	13	2	2	2	1	0	20
Mean duration (seconds)	2.9	0.6	1.2	1.5	1.5	--	1.54
II. Long lag group							
Number of reversals	21	5	2	1	3	1	33
Mean duration	10.5	5.3	1.8	.4	.3	.3	3.20
III. Mixed (long and short lag)							
Number of reversals	31	10	3	1	1	3	49
Mean duration	4.5	2.0	1.2	.7	.7	1.3	1.73

The presence of reversal errors in the performance of trained pilots in the use of the artificial horizon instrument (Pilot Study 3) shows there is a need for some workable training technique to eliminate these errors.

Summary Discussion of Laboratory Experimentation

Unquestionably the most important result of the entire experimental program was the finding that the natural response to roll motion differed very greatly from that to pitch motion with the same (large) horizon display. The response to yaw motion agreed with that for pitch. Pitch motion is shown by an up and down translation of the display, yaw motion by a side to side translation, and roll motion by a rotation of the display about some mid-point. There appear to be important and previously unsuspected differences in response to translational as opposed to rotational motions of such displays. The natural frame of reference for translational motion of the large articulated display is the content of the display; the natural frame of reference for rotational motions is external to the display.

Many large articulated displays for the use of operators of aircraft and other vehicles are being developed. The earlier discussion of contact analog and navigation displays has reference to two of the most important classes of such displays. If the above rule is applied to such displays there will be major changes in their design. Considering first the navigation display, the preferred design would have an "own aircraft" symbol that rotated with changes in aircraft heading, but with a map which would move under the symbol to show translational changes. The translational motion of a large well-articulated map need not interfere with the geographic frame of reference desired for navigational purposes if the natural frame of reference for translational motion of a large articulated display is the display content. If the map were rotated instead of the aircraft symbol, however, the relative motion situation would become confused, for the rotational motion of the map would not naturally be referred to the "own aircraft" symbol. The preferred type motion for a large map-type display, reasoning from the experiments with horizon-type displays, is therefore "north-oriented, moving map."

The preferred design for the contact analog display would require a partial abandonment of the contact analog concept. There is no reason to believe that the best way to present information about the position and movement of a vehicle to its operator is to show him something in a form akin to what he sees looking out of his vehicle. It would be unfortunate if the potential value of the integrated synthetic display were hurt by unnecessarily clinging to any such limited concept. This experimentation indicates that the contact analog as presently designed would be expected to cause difficulty to untrained subjects in its presentation of roll motion. This is in exact agreement with observations made in field studies of the instrument. It is quite likely that the same roll information when received in contact flight is also confusing to untrained subjects. Trainers equipped with contact analog instruments should be an excellent means of training to avoid such confusion in actual contact flight. In a display for instrument flight, it is possible to avoid the confusion due to roll motion entirely, however, by changing the display design. Figure 6 illustrates one means of doing this. It adds an aircraft symbol to the display to indicate roll. Pitch is shown by up and down motion of the horizon, as at present, with the aircraft symbol as an added reference. Such a display has an advantage aside from the fact that it eliminates the relative motion problem in presenting roll information; it is easier to generate.

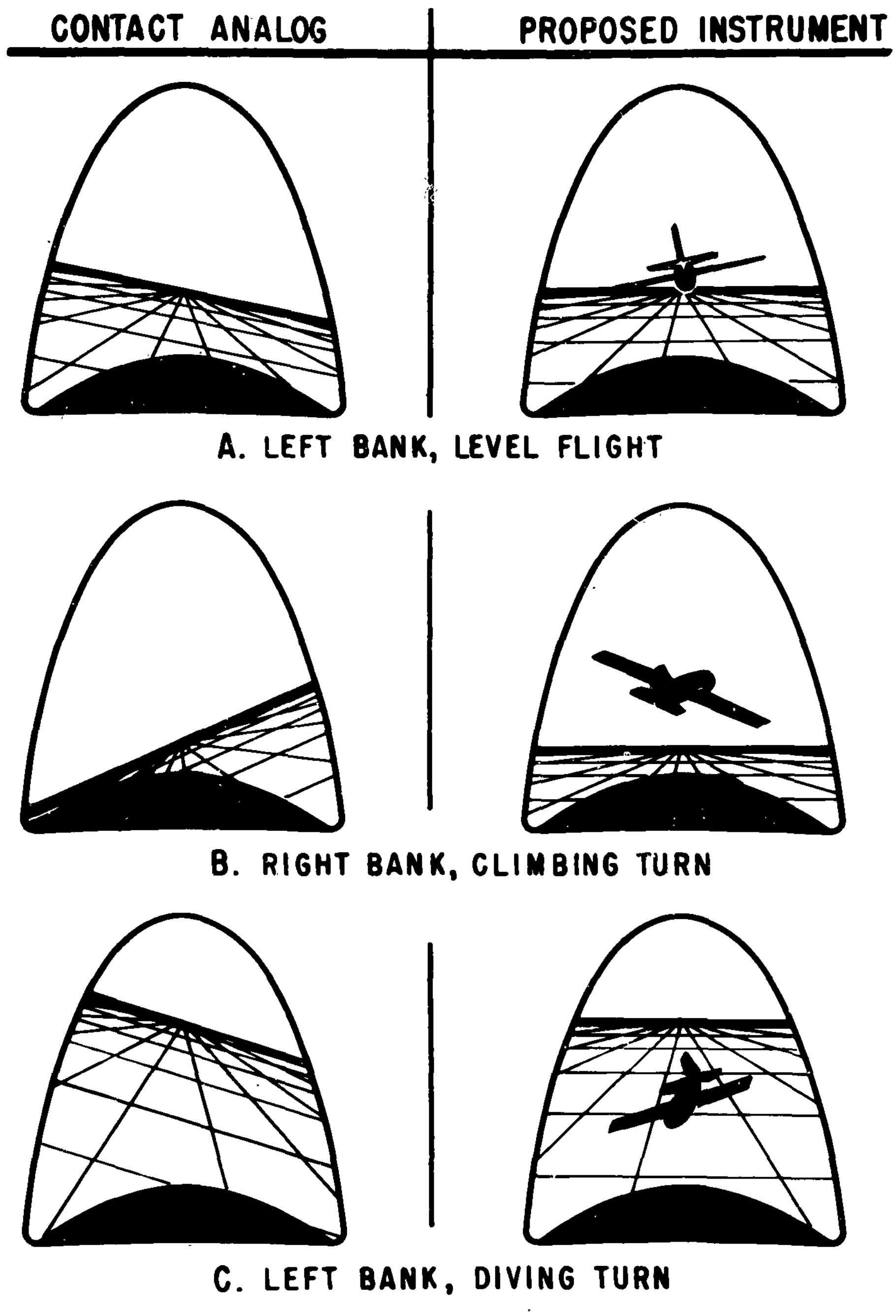

Figure 6. Existing and suggested means of presenting roll information on an integrated "contact analog" type display. Design of the suggested display should be such as to avoid reversal effects that make the aircraft appear to be flying toward rather than away from the user.

Future Research

Rather than list the numerous research implications of these studies, only four suggestions for additional research in relative motion and relative motion training will be made in closing:

1. The possibility that skill in performing visual intercepts is directly related to the use of relative rather than external frame of reference cues should be tested. If true, it is no doubt true for other relative motion problems, e.g., joining formation. Positive findings would have major importance in developing effective training techniques.

2. Dynamic navigation displays appear certain to come into extensive future use. All such displays involve serious relative motion problems. Experimentation should be initiated immediately a) to assist the Navy in selecting the best design for such a display, and b) to develop appropriate training techniques and devices for whatever display or displays the Navy may select.

3. Manual attitude control of manned satellites and spacecraft in three axes appears to be an extremely difficult task, one in which extensive training will be required. A major problem in three axis control is the motion relationships between vehicle, control, and display. Methods of three axis control should be investigated, and training requirements, including relative motion training requirements, detailed for the various proposed display-control systems.

4. Because aircraft indicators will probably continue to be designed such that reversal errors in roll remain an important training problem, a simple closed loop training device, providing an artificial horizon display having sudden unpredictable roll disturbances, and a roll simulator with variable lag characteristics, should be designed and tested for its effectiveness in eliminating roll reversals.

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APPENDIX A

FIELD STUDIES

Field studies of relative motion embraced three classes of situations: air-to-air intercepts, air-to-ground guided missile delivery, and relative motion problems in displays. Air-to-air intercepts were studied by detailed interview and discussion techniques, gathering information from some seventeen experienced pilots in Air Force interception squadrons. The air-to-ground missile guidance problem was studied analytically, with the added support of an analog computer simulation. Selected display problems were surveyed and analyzed. Each of the three classes of relative motion problems is discussed in turn.

A. Air-to-Air Intercepts

Air-to-air intercepts were studied by semi-structured interviews of seventeen Air Force pilots at Seymore Johnson and Shaw Air Force Bases. The pilots were at the time of interview assigned to fly jet interceptors, and many had, in addition, war-time combat interceptor experience.

Two techniques of interview were used. Ten subjects were interviewed individually, using the questions of Table 3 to structure the interview. The remaining seven were used to form two interview discussion groups, one of four and one of three members. In these groups, the questions of Table 3 were again used to generate discussion, and all responses that appeared of possible value were noted. The consensus is described below, along with important deviations from the consensus.

What is the frame of reference against which another moving plane is observed?

The primary frame of reference for observing another moving aircraft varies both among pilots, and with the same pilot under different conditions. A majority stressed their own aircraft as the principal reference frame. Scratches, windscreen struts, gunsight reticles, or other "own plane" factors which give relative motion information were cited as primary frame of reference determinates. Two pilots commented that they would be greatly

Table 3. Questions used in semi-structured interviews with seventeen interceptor pilots.

1. What is the frame of reference against which another moving plane is observed?

2. What factors determine this frame of reference, e.g., background (ground structures, clouds, etc.), foreground (especially own windscreen), and conceptual factors (knowledge of type of plane, speed, etc.) received from other sources?

3. How does loss of background structure affect accuracy of judgment of other plane's motion? (e.g., a homogeneous cloud layer vs. a well-structured background)?

4. How does the size and shape of the other aircraft contribute? (e.g., If the plane were a sphere, how would it affect an intercept performed relying on visual cues? If the other plane were visible only as a point of light flying against a uniform black, starless sky, how would it affect the difficulty of an intercept?)

5. How does instrument information affect perception of the other plane's movement?

6. What maneuvers by the other plane are most difficult to note and correct for when relying on visual contact to intercept?

7. What additional information would be most helpful to the interceptor pilot in performing his task?

handicapped by looking out through a clear structureless plastic bubble. At high altitudes, or against a featureless background, the "own aircraft" reference frame was stronger still. The stress by almost all pilots on rate of closure information also points to a relative frame of reference.

A large minority of the group relied principally on an external reference framework. This group tended to stress background above foreground (windscreen) frame of reference cues. These pilots maintained an "outside-in" external reference frame more strongly than the majority. The differences between the two groups are not clear-cut, however. Almost all pilots agreed on the importance of cues that contribute to each kind of reference frame. It appears, on the basis of these interviews, that the frame of reference utilized in flying an intercept may vary according to the cues available, and according to the predilection of the pilot. Some interviews were impossible to classify on the frame of reference question for these reasons.

None of the pilots interviewed regarded the other aircraft as the frame of reference for motion of their own craft. This theoretical relative motion framework may, therefore, have little practical significance.

<u>What factors determine the pilot's frame of reference?</u>

Pilots flying intercepts tend to make use of whatever information is available to them. Pilots who lay stress on "own plane" as a frame of reference tend to stress "own plane" cues such as:

1. Canopy, frame, and nose of own aircraft;
2. Windscreen scratches, splotches, or other "accidental" structure against which changes in position and size of other aircraft can be viewed;
3. Gunsight reticle, especially in providing size and size change cues of distance and closure rate.

The horizon as a frame of reference was stressed by pilots who were emphasizing "own plane" frame of reference cues as well as by those emphasizing external or background cues. One of these pilots said:

> "My canopy and the horizon make up the frame of reference against which another moving plane is seen."

The "own aircraft" frame of reference is not entirely relative, therefore, but is fixed with respect to the plane of the earth's surface.

Almost all pilots, but especially those who stressed the external "outside-in" reference frame, felt background cues were important in perceiving another plane's motion. A few of these pilots pointed out the importance of such cues in giving a pilot better feeling for the motion of his own plane.

How does loss of background structure affect accuracy of judgment of other plane's motion?

Since background cues were believed to be of importance in perceiving another plane's motion, their loss naturally was said to degrade motion perception. Since background cues are often weak or absent, especially at high altitudes, this judgment was made on the basis of experience. Uniform haze background or uniform blue sky background makes an intercept more difficult, especially if no horizon is visible, and in some circumstances results in a tendency toward vertigo.

How does the size and shape of the other aircraft contribute?

Pilots agreed that shape and size, and changes in shape and size of the other aircraft were enormously important in performing visual intercepts. Pilots went into detail as to what cues were important. Many mentioned the shape of the tail section. Knowledge of the actual shape of the aircraft was stressed as important in interpreting what is seen. Some indicated that swept-wing aircraft were especially difficult because it was easy to misjudge their heading.

There was general agreement that loss of shape cues (e.g., in intercepting a sphere) would make the visual interception job extremely difficult, and in many cases impossible. If the sphere were replaced by a point of light against a featureless ground, so that not only shape cues but also size and size change cues were absent, the situation would become even more hopeless, with the added complication of autokinesis and vertigo.

How does instrument information affect perception of the other plane's movement?

Most but not all pilots agreed that instrument information per se was rather unimportant in perceiving the other plane's motion. This is not to say that awareness of what their own plane is doing is not important, for it clearly is. Pilots have many cues as to what their own plane is doing, however, in addition to their instruments. Their own control movements are a major factor, of course.

Pilots mentioned air speed, altitude, and heading instruments as the ones which sometimes were helpful for ascertaining the motion of the other craft.

One pilot stated that he sometimes used these instruments to hold his own plane in a constant position, so that any motion he observed of the other plane relative to him was due to the other plane and not to him. Two pilots commented on the need for good knowledge of own speed in judging the speed of another aircraft. Another mentioned holding a constant level altitude (with the help of instruments) to determine another plane's altitude.

What maneuvers by the other plane are most difficult to note and correct for?

There was an almost unanimous opinion that speed changes are the most difficult maneuver to note and correct for. Gradual changes in altitude were also mentioned frequently. Gradual changes in heading, and sudden changes onto a head-on near collision course were also mentioned as providing difficulties, the latter because it is difficult to judge whether the plane is turning inside or outside of your course.

There was an emphasis by most pilots on the problem provided by gradual as opposed to sudden changes. Gradual changes in speed, altitude, or heading all were considered more difficult to note and correct for than quick changes.

What additional information would be most helpful to the pilot flying visual intercepts?

Most of the pilots said they would like to have rate of closure, target speed, and target heading information, this order corresponding to the frequency with which these items were mentioned. Several indicated they would like to have target range information. Also mentioned were target altitude, optimum angle of attack, and a radar warning of planes at an angle outside the visual field. One pilot felt a major improvement would be to redesign the instrument panel so that the pilot could spend more time looking out.

Additional Comments

In addition to answers to the questions described above, many of the pilots had comments about the intercept job that were of interest. Two pilots volunteered that experience was the most important factor by far in flying intercepts. One said that the task was "nine-tenths" one of experience.

Several pilots commented that condensation trails were extremely helpful in flying intercepts.

One pilot commented that there were large individual differences in ability to detect planes prior to interception. He felt that detection was easier when the plane to be detected was to one side of the line of sight rather than centered.

One pilot commented that a uniform grid drawn on the windscreen would be helpful in showing the relative motion of a target aircraft. This is of special interest in view of the comments by others on the helpfulness of windscreen structure, scratches, and gunsight reticles.

Discussion

Perhaps the most important general finding gathered from the interviews was that the frame of reference used in flying an intercept differs among pilots. While most have developed to a large degree an "inside-out" relative point of view, and rely most heavily on relative cues, a sizeable minority still operate principally on an "outside-in" geographic basis.

In the initial relative motion study in this series, (Runyon et al, 1958) it was suggested that the less experienced person would attempt to utilize an "outside-in" frame of reference in a relative motion situation, and that this might be harmful to the proper execution of specific maneuvers. The comparative ability to fly intercepts of pilots utilizing the two kinds of frame of reference is of interest in the light of this hypothesis. No means of assessing this ability was possible. There did appear a tendency for the higher ranking officers to fall into the "inside-out" relative frame of reference group, but there were not enough cases to justify a statistical test of the hypothesis. This is an area of potentially fruitful research, however. If, in fact, the more skilled and experienced pilots utilize a relative frame of reference while less skilled and experienced do not, this fact has important implications for the design of training programs and training devices to improve this skill.

In the Phase II relative motion report (Kelley et al, 1959) an experiment was reported on the estimation of the path followed by a moving model aircraft as compared to that of an equally large sphere, each flown at eye level against an almost featureless background. The results showed that the motion of the model aircraft was judged much more accurately than was that of the sphere. This experiment gave rise to question 4 of Table 3, as to the importance of shape and size of the other craft. The unanimous response is in complete accord with the results of the experiment, and confirms that shape cues are enormously important in flying visual intercepts. This fact should weigh heavily in training pilots for this task.

B. Air-to-Ground Missile Guidance

Air-to-ground missiles which are guided by the aircraft pilot pose relative motion and relative motion training problems of special difficulty. Flying two vehicles at once must be difficult at best, and air-to-ground missile delivery is apt to be carried out under conditions far from ideal. In order to render this problem into form suitable for analysis, some assumptions about task were necessary. It was assumed:

1. That the aircraft would fly a straight-line constant-speed course during delivery.
2. That the missile would fly (a) at a constant speed or (b) with an initial spurt followed by a deceleration.
3. That the missile would be brought to, and guided in along, a line of sight track.

Analysis of possible missile courses showed that with any delivery other than head-on target or tail-on target, the line of sight missile track is a curving course which is not pointed toward the target until the instant of impact. Figure 7 illustrates this. The curvature of the missile course is gradually reduced as the missile approaches the target with ninety degree, or greater, initial delivery angles. With initial angles smaller than ninety degrees, the curvature of the missile course will be less at the start, and will increase as the plane approaches right angles to the target. The point of sharpest curvature of the missile track will not be at the start, but somewhere in the middle of the track.

The solid lines in Figure 7 show constant speed missiles traveling with speeds of 2 and 1.5 times that of the aircraft. The dotted lines represent tracks of missiles that are decelerating in proportion to their speed. Because it initially has greater speed than the constant velocity missile, the decelerating missile angles more sharply towards the target at the outset. In late stages of the flight its slower speed results in the reverse effect, however.

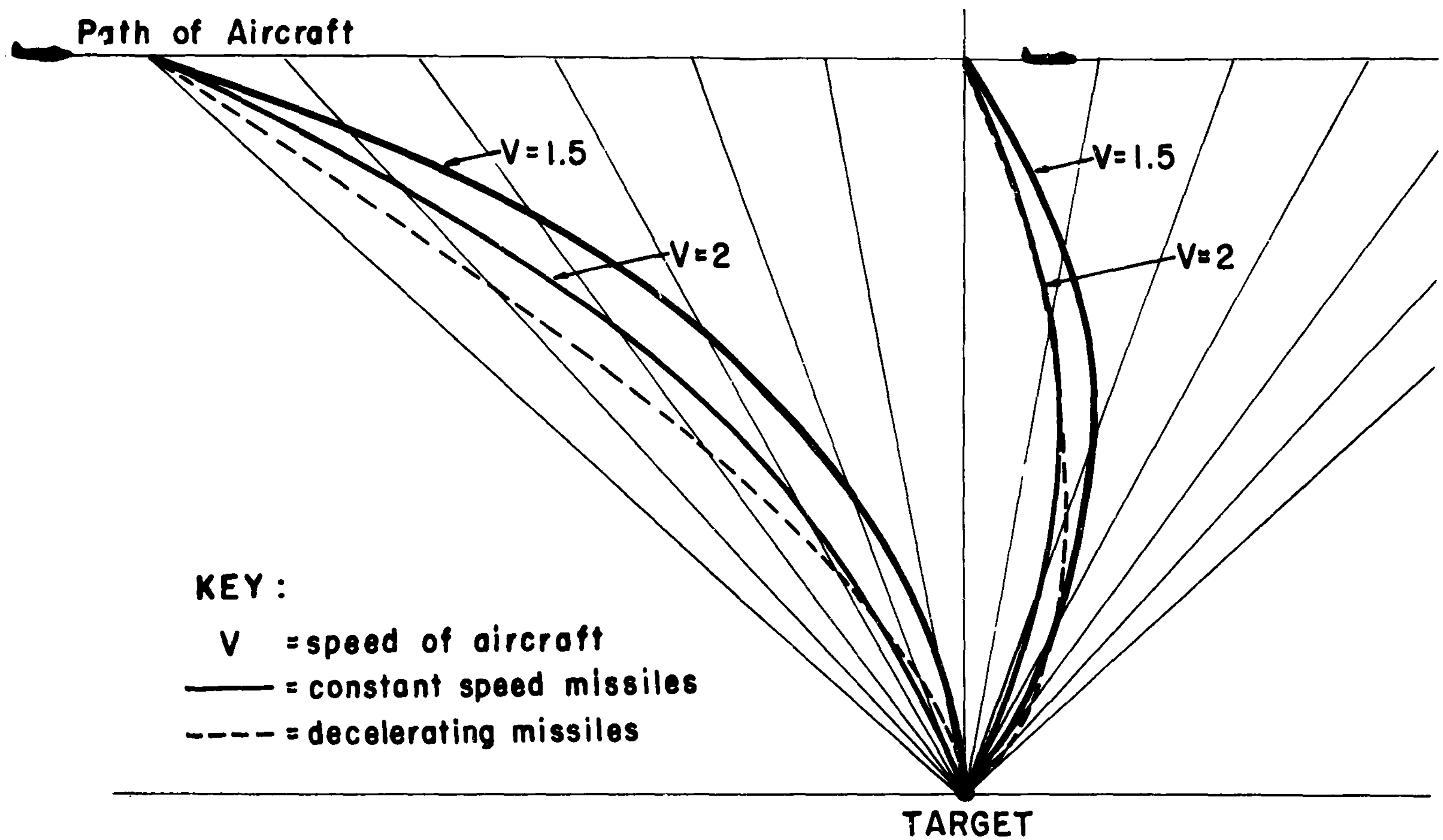

Figure 7. Tracks of guided missiles steered from aircraft to target along line of sight courses.

Decelerating missiles follow a track that becomes more curved near the target as compared with constant velocity missiles from the same launching point, having the same average speed.

From a relative motion standpoint, the simplest delivery problem by far occurs with a head-on target or tail-on target firing. These are the only straight line trajectories under the conditions described. Not only is the relative motion problem much simplified with head-on or tail-on delivery, but these are the only cases in which, if the pilot is interrupted during the guidance phase, the missile will be directed at the target, and may nevertheless score a hit. With every other delivery, the missile is never pointed at the target until impact.

In order to develop a better feel for the air-to-ground missile problem, a simulation was set up in the laboratory. A seventeen inch cathode ray tube was used to represent the pilot's field of view. The target was a mark at a fixed location on the face of the oscilloscope. The CRT display represented missile position with respect to the target by means of a spot of light which moved in two dimensions, and decreased in size and brightness during the problem as the missile sped away. The spot was controlled by a stick having two degrees of freedom, operating through analog computing circuits representing the missile dynamic characteristics. Distance of the missile was also represented by an appropriate reduction in missile response rate on the display, corresponding to the effect of linear perspective (lateral motions appeared faster when close to launching, slower when farther away). In addition, it was possible to program missile deceleration during the run, changing the dynamic characteristics of the missile appropriately with the decreasing speed. Runs lasting between twenty and forty seconds were made with varied initial errors and error rates. At the end of a run, the spot representing the missile brightened abruptly and the computer went into "hold," at which point the miss distance in terms of display coordinates could be noted. The experimenter practised several hours with this simulation, and also employed informally two other individuals experienced in tracking as subjects on the same problems.

It was found that precise control in the early phases of the problem was enormously important. When initial errors and error rates could be corrected accurately, the later phases of the problem caused no difficulty. However, when the initial errors and/or error rates were not corrected accurately and promptly, there proved to be a great deal of difficulty, and large miss distances frequently resulted. Correction for error rates proved harder than correction for position errors only.

In the case of a decelerating missile, early correction of errors proved even more important. With the most difficult problems (large initial errors and error rates) the first few seconds of a run determined whether or not there would be a low miss distance. Quick perception of error rates played a large role in the solution of these problems.

From this study it is concluded that the most critical phase of the air-to-ground guided missile delivery under the conditions specified above is the first phase of the problem. Training should emphasize the skills necessary to make correct responses at the very start of a missile's flight. An essential feature of this training is an appreciation of the relative motion of the missile with respect to the aircraft, including the ability to judge missile motion accurately, and make appropriate corrections quickly.

C. Relative Motion Problems in Displays

The study of relative motion problems in vehicular displays disclosed that there are two principal areas in which relative motion problems are particularly serious; namely, vehicle attitude displays and dynamic navigation displays, including artificial horizon displays, and the new problem of attitude displays for spacecraft. These areas will be discussed in turn.

1. Vehicle attitude displays

The earliest major relative motion problem in a display to be recognized in human engineering research is that of the artificial horizon. The artificial horizon is but one example of the more general problem of the display of attitude information to a vehicle operator. Any attitude display can cause a relative motion display problem.

A display of attitude represents to the vehicle operator the angle of his vehicle with respect to the direction of some reference plane or axis, e.g., the horizontal plane, or the direction of the course along which he is traveling. When the operator has cues of attitude in addition to those provided by the display, when he modifies his attitude by the manipulation of controls, or when attitude display information must be coordinated with information from other related displays, the problem can become quite complicated. Frequently, all of these conditions are present.

In order to display the attitude of a body with respect to a frame of reference, the attitude and frame of reference are both present or implicit in the display. When the display background and framework (possibly including the instrument panel) is used to represent the vehicle frame of reference, and a moving display pointer, scale, or other element represents the vehicle attitude, the display is of the form sometimes referred to as "outside-in." The display in this case is sometimes an outline of the vehicle. When the moving element of the display represents the frame of reference, and the background or panel represents the vehicle, as in the artificial horizon-type instrument, the display takes the form sometimes referred to as "inside-out."

Human engineering research has overwhelmingly supported the "outside-in" display configuration (Fitts, 1951). The previous report in this series (Kelley et al, 1959) pointed out that if a display were designed so that the content or moving elements of the display formed the natural frame of reference for the operator, while the vehicle was perceived as moving with respect to this frame of reference, the "inside-out" form of instrument would be called for. Some of the new large CRT type displays, e.g., the ANIP contact analog displays, were thought to fulfill this condition. Figure 1, page 10, illustrates such a display. Contact analog displays were examined and simulators flown containing such instruments in El Segundo, California, at the Douglas Aircraft Company, and at the Bell Aircraft Corporation in Fort Worth, Texas. It was expected that the "inside-out" frame of reference used by these instruments would be the correct one. Observations failed to confirm this expectation. Although pilots (who are trained on the "inside-out" horizon display) respond correctly to the contact analog, untrained subjects make frequent reversal errors. This appeared to be especially true in the control of roll.

Because the contact analog is a large structured display, this observation was contrary to expectation, and led to reexamination of the hypothesis. Is it true that the display content can sometimes become the frame of reference, and the vehicle appear to move with respect to it?

An affirmative answer to this question was obtained by reference to Witkin's tilting room apparatus. In his tilting room experiments, Witkin employed a small room that could be rotated about a roll axis. His subjects sat facing into the room in a chair that could be tilted independently of the room. Under these circumstances the illusion of tilting could be induced in upright subjects when the room was tilted (Asch and Witkin, 1948, Witkin and

Asch, 1948, Witkin, 1950 and 1952). Considering the room as the "display" and the chair as the "vehicle," it follows that the display becomes the frame of reference with respect to which orientation of the vehicle is perceived.

There is a difficulty in applying Witkin's research to the attitude display problem, because Witkin was concerned with problems of orientation rather than movement in space, and his observations were gathered when his subjects were in stationary positions. For this reason, a trip was made to Dr. Witkin's laboratory to discuss the effect of motion in his experimental arrangement and to try the equipment.

Dr. Witkin's reports on experiences of subjects in the tilting room agreed with the reaction of the three persons on this project who visited the laboratory and served as subjects on the apparatus. Roll motion of the tilting room induces in the subject the experience of self motion in the opposite direction. Thus, if the room is considered the "display" and the chair the "vehicle," the display can certainly become the frame of reference with respect to which the vehicle appears to move. The observers agreed that if they were operating a control which would vary the angle of the chair, the "natural" control response in consequence of the induced motion of the chair would be of the "inside-out" variety. Therefore the hypothesis that the large structured display can become the frame of reference with respect to which a vehicle moves is confirmed for an extreme case. The need for research to see whether this hypothesis held for displays of practical size appearing on a vehicle panel was evident. The experimental program described in the Appendix which follows is addressed, in large part, to this problem.

Despite the tilting room results, one result of the field studies of vehicle attitude displays was to cast further doubt on the choice of "inside-out" type displays, even in the one situation where they had previously appeared justified; namely, the contact analog. It is quite possible that the contact analog display would be improved if it were redesigned to give an "outside-in" presentation of attitude, although this would contradict the fundamental concept implied by the name "contact analog." The concept is, in fact, open to question. It may not be true that the best way to present information about the position and movement of a vehicle to its operator is in a form akin to what he sees looking out of the vehicle. It may be more effective to present to him information akin to what an observer outside his vehicle would see. If the operator of an aircraft or submarine were supplied with an "outside-in" display of his own vehicle and its surrounds as viewed from a point external to the vehicle, and if this display were developed to approach the level of sophistication applied to contact analog instruments, a superior display might well result. The fact that it is frequently easier to perceive accurately the motion of another aircraft than that of your own supports this line of reasoning.

2. Space-ship attitude displays

Although it has been known for years that the usual aircraft displays are less desirable for training new pilots than "outside-in" instruments, any change is difficult to realize because of the problem of transitioning present pilots and perhaps converting present aircraft. The development of manned satellites and spacecraft provides the opportunity to use the knowledge about attitude displays developed in aircraft research, but not applied. Some of the proposed displays for space vehicles are adaptations of aircraft instruments and carry over their faults. New forms of displays, however, are being considered. One such display is the spherical attitude indicator developed by Lear. This indicator provides either two or three axis attitude information. The X-15 panel includes a three axis indicator of this sort. Figure 2, page 12, illustrates the instrument. The moving sphere represents frame of reference information while stationary markings represent the vehicle, so this is an "inside-out" presentation. It can probably be used without great confusion by pilots, who are trained on the "inside-out" display of pitch and roll afforded by the aircraft artificial horizon. However, the instrument is likely to result in increased training time and increased probability of reversal errors for non-pilot operators. The "inside-out" display concept is not recommended for any but very large displays when there are satisfactory alternatives. It would appear feasible to convert the Lear instrument to an "outside-in" configuration, in which the vehicle were outlined on the moving sphere, and the frame of reference were represented by stationary scale markings and by the surrounding panel. Such an instrument should be a major improvement from the standpoint of our knowledge of relative motion.

In tracking experiments conducted in the laboratory of Dunlap and Associates, Inc., it has on occasion been desirable to present two and three axis attitude information to subjects operating simulated vehicles. Original presentations were made using separate meters for each axis. These proved difficult to use, and the need for an integrated display became apparent. A highly useful simple integrated display was developed for oscilloscope presentation. Figure 3, page 13, illustrates this display. A horizontal line with a bright spot in the middle forms the moving element of the display.

The element moves up and down (y axis) to show pitch, to either side (x axis) to show yaw, and tilts (angle of symbol to x axis) to show roll. Since the moving display element represents the vehicle, this is an "outside-in" presentation. Experience in the laboratory has shown it to be an excellent display in terms of ease of learning, absence of reversal errors or difficulties in interpretation, and unity of the triplex presentation.

A further improvement on this display was developed jointly by Mr. George Berbert of Dunlap and Associates, Inc., and Dr. Robert Knaff of the General Electric Missile and Space Vehicle Department. Their display adds to the position symbol illustrated in Figure 3 a three axis rate indication formed by an ellipse which will just contain the position symbol. When the ellipse is centered over this symbol, and the major axis of the ellipse coincides with the line portion of the position symbol, there are zero roll, pitch, and yaw rates. The x and y deviations of the ellipse from the position symbol show yaw and pitch rate, respectively, while deviations of the axis of the ellipse from the line of the position symbol indicate roll rate. The vehicle can be halted in any attitude by "flying" the ellipse over the position symbol. In addition, the vehicle (position symbol) will follow the ellipse (rate symbol) so that if the ellipse is held at any position on the scope, the position symbol will go there. Evaluation and application of this display is being carried forward in the Human Dynamics Laboratory of the bio-astronautics operation of the General Electric Missile and Space Vehicle Department. This writer believes this may be the most effective three-axis attitude display yet developed.

A major advantage of an oscilloscope-type display is its flexibility. It is easy to vary scale factors, for example, and to add additional signals when desired. For example, command or director information telling the operator what control movement to make to achieve a stable attitude correction can be added to a basic attitude display with little difficulty when the display is presented via an oscilloscope.

3. Dynamic navigation displays

The second type of display beset with serious relative motion problems is the dynamic map-type or navigation display. There are many advantages in presenting a pilot with a map-type display on which his own and other aircraft are displayed, their positions continuously and automatically being updated. In certain military flight situations the potential value of such a display is enormous, e.g., in interception. It is also a display of potential value in accident prevention and other air traffic control problems. Problems in the design of such a display include the following:

1. If such a display is north-oriented, the direction of an "own aircraft" symbol on the display would vary with heading. Thus the symbol for a southbound aircraft would be flying in the opposite direction to the actual aircraft. This would tend to confuse control-display relations. Movement relations among the displays on the panel would also change as an aircraft changed heading. A southbound plane turning west would be shown by a symbol moving to the left on this kind of map display, while a contact analog display would indicate a banking right turn.

2. If the display were heading-oriented, so that the top of the display always represented the direction the aircraft were flying, then the map for a southbound aircraft would be upside down. Printing and symbols might appear in any orientation.

3. If the display were heading-oriented, the apparent motion of other aircraft would be the result of their true motion plus a component due to change in heading of own aircraft. This would present a confusing picture to a turning aircraft, and would reduce the effectiveness of the display for maneuvering, e.g., in interception or collision avoidance.

4. If the display were a stationary map across which one's own aircraft moved, the display would have to change periodically to prevent the aircraft from leaving the map.

5. If the map moved under the display, the forward motion of "own aircraft" would result in an apparent motion of other aircraft on the display in the opposite direction.

6. In the helicopter situation the problem is greatly complicated by the fact that the vehicle is not constrained to move along its body axis. Thus the direction of flight may be different from, even opposite to, the vehicle's orientation at a given time.

Considering only the fixed-wing problem, four types of display could be used in terms of motion relationships:

1. North-oriented, moving plane;
2. North-oriented, moving map;
3. Heading-oriented, moving plane;
4. Heading-oriented, moving map.

The first of these might be considered a completely "outside-in" reference; the last, completely "inside-out." The other two are mixed types. The first is the only one of the four showing true motions of own and other aircraft against a stationary geographic frame of reference. When these motions are complex, and when maneuvering is carried out entirely on instruments, this display should be superior. It should be relatively simple to perform a proper intercept on this display, for example, assuming altitude were well coded. An intercept could prove difficult on the third or fourth type of display, particularly of a maneuvering target.[1]

When the true motions of other aircraft are less important to the pilot, the advantages of the fourth type of display, the "inside-out" presentation weigh more heavily. This display coordinates most readily with what the pilot sees in contact flight, which is, after all, an "inside-out" picture. For the same reason, it coordinates best with the contact analog instrument as it is presently designed. It also creates the least problem in terms of the relations between the display and controls, and the other displays. The seriousness of the problem of reading a map upside down must be evaluated, however. It is the opinion of the writer that some pilots would find this very objectionable.

In the field trips to Douglas Aircraft and Bell Aircraft, human factors personnel were most concerned with the above described problems in navigation display design, since development of such displays for use with the contact analog was in progress at both companies as part of the joint Army-Navy Instrumentation Program. Since a requirement of these programs was compatability with the contact analog, the "inside-out" and mixed type of navigation displays were favored. Problems associated with these displays in helicopter flight are discussed by Dougherty (1959).

1 Experimentation to be described in the next Appendix will be interpreted as a recommendation for the second (north-oriented, moving map) type of display.

A dynamic navigation display was simulated in the laboratory of Dunlap and Associates, Inc., using black and white motion picture photographs of an aerial map, on which aircraft symbols consisting of arrows were superimposed and moved, using animation techniques. The situation represented was of several maneuvering aircraft in a crowded air space. (See Figure 4, page 16) Aircraft velocity was represented by the length of the arrows, and the distance from the base of the arrow to the tip was the distance that would be flown in thirty seconds. The display was north-oriented, with a stationary map that jumped to a new location when the "own aircraft" symbol crossed out of an inner circle on the display. The inner circle had half the diameter of the total display. The display was completely "outside-in" in type.

Observers felt that this display was a good one for navigation and maneuvering purposes. It was easy to interpret, and would, it was felt, prove easy to fly by. There was the possibility of confusion on direction of control movements with southerly courses, there was a possible difficulty in coordinating the display with other displays and with visual contact information, and there was the possibly unnecessary "jumping" of the display to new locations as the symbol crossed most of the map. (The latter difficulty would be absent in a moving map display.) These difficulties need experimental study. In the absence of such studies, this form of navigation display can be recommended as a satisfactory one for maneuvering and navigation purposes.

APPENDIX B

LABORATORY STUDIES OF RELATIVE MOTION PROBLEMS IN DISPLAYS

The experimental program dealt with the most frequently encountered and perhaps least well understood relative motion problem in vehicular displays, the display of attitude information. A series of pilot studies of various aspects of the problem was carried out, after which some of the most interesting hypotheses suggested were tested more rigorously by means of two controlled experiments. Each study is described and discussed briefly in the pages which follow, while a summary discussion covering the whole experimental program has been presented in the Brief.

All of the studies were carried out using an aircraft joystick for vehicle control, and varying the display and canopy as described. All of the displays represented the horizon with various degrees of realism. Experiments dealt with up and down motions of the horizon display, indicative of aircraft pitch, and banking motions of the horizon display, indicative of aircraft roll. Control-display relations were those of standard aircraft. Subjects were trained briefly on the relationship between movements of the joystick and the subsequent response of the vehicle, and were questioned after experimental sessions to see if there had been any confusion on this point. There was no problem on this account, as far as could be ascertained.

For every deviation of the horizon, subjects could make either an appropriate response, which would move the simulated aircraft so as to reduce the deviation, or an inappropriate response, which would make the deviation worse. "Appropriate" response in the context of this experimental program is synonymous with "inside-out" type of response, since only the "inside-out" response is appropriate to a moving horizon-type display. An "outside-in" response, which is more natural under most circumstances, is always an inappropriate response in the context of these experiments.[1]

[1] By "inside-out response" is meant an appropriate response to an inside-out display, in which a moving element (horizon) represents a stationary frame of reference and the vehicle (panel and markings) is seen to move in the opposite direction relative to that "fixed" element. By "outside-in response" is meant an appropriate response to an outside-in display in which the moving display element represents the vehicle.

A. Pilot Studies

Pilot Study 1: Display Size

In the previous report in this series (Kelley et al, 1959) it was suggested that a large horizon display might result in a control movement opposite in direction to that brought about by a small one. This suggestion was based on the hypothesis that with the large display, the content of the display could become the frame of reference with respect to which the vehicle's motion was perceived. The first pilot study was a crude test of this suggestion. It is well known that with a small horizon display, responses by an untrained subject tend to be inappropriate. (This fact has been verified many times in our own laboratory.) The initial test, therefore, required only that the natural response of naive subjects to a large horizon display be ascertained.

Purpose

The purpose of the study was to see if naive subjects would make an appropriate response to roll motion indicated by a large schematic horizon display.

Subjects

Six adults of both sexes, none of whom had piloting experience, served as subjects.

Equipment and Procedure

A control stand on which a chair and joystick were mounted faced a large ground glass screen, onto which the display was back projected. The display was round, thirty-six inches in diameter, at eye level, and perpendicular to the subject's line of sight. The subject's eyes were approximately twenty-seven inches from the center of the display, the total display subtending sixty-seven degrees of visual angle.

The horizon was produced by a projector and a manually operated shadow-casting device, producing an unstructured bright "sky" above and an unstructured black "earth" below to represent level flight. Figure 5, page 17, shows two views of the display.

Each subject was instructed which was earth, horizon, and sky on the display, and was taught how to cause the "aircraft" to roll (or bank) or to correct for roll, by moving the stick. He was told to attempt to maintain level flight on each experimental trial by moving his control stick quickly as soon as the display indicated his aircraft was banking. The display was level at the start of each trial, and within six seconds began tilting rather quickly. As soon as the subject responded, the display was turned off, so there was no indication as to the result of the control action. There were eight trials in randomized sequence.

Results

All responses by all subjects were "inappropriate." There was no tendency for any of these naive subjects to make control movements different from the natural response to a small display.

Some subjects tilted their bodies in the direction of the movement of the display, a phenomenon seldom occurring with small horizon displays.

Discussion

The hypothesis that with a large display the display content would become the frame of reference and the vehicle would be perceived as moving with respect to this frame of reference was not substantiated under the conditions described. The experimenters ran each other as subjects and felt that the distractions in the laboratory, the lack of any illusion of being in a vehicle, the unrealistic horizon display, the quick movement of the display, and especially the lack of a simulated vehicle that could have roll movement were important factors in the results. A more realistic situation was required to test the hypothesis.

An informal addendum was made to this study. After running each subject the experimenter explained to them that their responses were inappropriate, drew a picture of a banking aircraft showing what the horizon looked like, and what must be done to correct it. All subjects appeared to understand. The experiment was then repeated. Three subjects completely reversed their responses, making all appropriate responses, one subject made six out of eight appropriate responses, and two subjects made three out of eight appropriate responses. However, the tendency to make the inappropriate response was very strong, even in the three subjects making all appropriate responses. On questioning, two of these three subjects had followed a self-imposed rule to move the stick the "wrong" way, or the "same" way as the display.

Pilot Study 2: Display Size and Rate of Movement

Purpose

The purpose of the study was to further test the hypothesis that a large display can induce a control movement opposite that of a small display, under more realistic conditions than those of Pilot Study 1.

Subjects

Three experimenters used each other as subjects. None had any piloting experience.

Equipment and Procedure

A U. S. Naval aircraft pilot seat and joystick were mounted on a raised platform which could be tilted up to ten degrees in either side. A pilot's compartment was constructed using black cloth over a wooden framework, so that subjects were completely isolated from visual contact with the laboratory outside the compartment. The screen was used for the display, but instead of a shadow caster, a Kodachrome transparency of an actual horizon scene was employed. This was back projected onto the ground glass screen using a projector having a wide angle lens. This projector sat on a table attached to the pilot's enclosed compartment, so that as the compartment tilted, the projector tilted with it. The projector could, in addition, be tilted independent of the compartment, to produce the appearance of roll on the display.

Four series of trials were given each subject, display conditions being varied for each series. The display showed level flight at the outset of each trial. After a few seconds a bank was initiated at one of three different rates, the direction determined by a randomizing procedure. The rates used were 2-1/2, 5, and 10 degrees per second on series 1, 2, and 3, respectively. The pilot's compartment was rocked slightly in between the trials of the first three series, but not during a trial. In series 4, however, the pilot's compartment was tilted simultaneously with and in the same direction as the display, which moved at five degrees per second. As soon as a subject made a response, the display projector was turned off, to prevent any learning effects.

Results

Despite the vastly improved realism of the display, none of the subjects made appropriate responses under any of the four conditions except for an occasional atypical response. All felt that the realism of the situation was very compelling. The principal thing detracting from this realism was the lack of the expansion on the display resulting from forward motion.

A supplementary series of trials was carried out using a 16 mm Kodachrome motion picture of the horizon taken with a zoom lens, so as to provide an expansion pattern realistically simulating forward motion of an aircraft. This provided a wonderfully realistic simulation, but tilting of this display still did not result in "appropriate" control responses from the subjects.

Discussion

Using a large, beautifully articulated, realistic display and apparatus in which subjects could themselves be tilted, appropriate control stick movements still occurred only rarely. It will be recalled that when using Witkin's tilting room apparatus, the experimenters were confident that an "appropriate" response would be made. For this reason, the display size required to induce an appropriate response to roll under realistic conditions may be extremely large, perhaps even to the extent of occupying the whole of the visual field. From a practical point of view, such a display would rarely be feasible.

Pilot Study 3: Pilots vs. Non-Pilots

As a matter of interest, the apparatus of the previous study was utilized in comparing the responses of five pilots and five non-pilots, given identical problems.

Purpose

The experiment was designed to compare the response of pilots and non-pilots to the banking motion of a large, realistic horizon display.

Subjects

Subjects were five flyers, none of whom flew more than occasionally now, but with flying experience ranging from a few hours (one subject) to several hundred hours, and five non-flyers of similar ages and backgrounds.

Equipment and Procedure

The same apparatus as in the previous study was used, with the Kodachrome color slide of a horizon scene as the display. Three series of eight trials each were given as follows:

1. Started in a bank of 5° or 10° (four trials at each position) which was increased gradually.
2. After five seconds of level flight, the display banked at 2-1/2° or 5° per second (four trials at each rate).
3. Started in a bank of 10° or 20°, diminishing toward (and past) zero at 2-1/2° or 5° per second, respectively (four trials with each rate). Subjects were told to wait until the display was nearly level, then to move their stick so as to stop the motion.

The direction of motion for each trial was determined by a randomization procedure. Each trial ended as soon as the subject moved his control stick, at which moment the display was blanked by turning off the projector.

At the conclusion of the regular run by each non-pilot, the subject was given eight additional trials using one-second display exposures of the horizon in right or left five, ten, fifteen, or twenty degree banks, in random order. After completing this series, the non-pilots were asked to draw their aircraft, showing the direction of its bank for a given display condition (20° bank).

Results

The pairs of conditions within each of the three series of trials showed such small differences in all cases, the results were combined within each series. These are summarized in Table 1 on page 19.

The final series of eight one-second exposures given to non-pilots only resulted in 17.5 per cent appropriate responses. Four of the five then drew the aircraft showing the direction of bank incorrectly for the condition shown on the display.

Discussion

Great differences are obvious in the responses of pilots as compared to non-pilots. This should be expected from the overwhelming preponderance of inappropriate responses by non-pilots on the previous studies.

It is interesting and important that there were many errors on the part of the pilots. This indicates that the roll display is a source of reversal errors for pilots, and perhaps is a safety hazard. The more errors occurred in series 2 and 3, where the movement of the display rather than its initial position is the critical cue. The fewest errors occurred in series 1, where the initial position and movement of the display would, taken separately, each result in the same control movement.

The pilots felt the display was excellent, actually providing a larger and better horizon view than that seen from moving aircraft.

It is noteworthy that non-pilots not only consistently made inappropriate responses, but also believed their plane to be banking in the direction opposite to the true one. This corroborates the difficulty some of the subjects in Pilot Study 1 had in learning the correct response. The tendency of the naive subject to make an "outside-in" response to the banking of a horizon indicator is much stronger than the experimenters had supposed.

Pilot Study 4: Limited Visual Field

This experiment imposed an additional control on the conditions of Pilot Study 2 by limiting the visual field of subjects to include only the display itself.

Purpose

The study tested the natural response to a large horizon display of roll by naive subjects, with the visual surround of the display eliminated. The hypothesis was that the surround might prevent the display content from becoming the subject's frame of reference.

Subjects

Two young adults with no flying experience (and no previous experience in these experiments, of course) were subjects.

Equipment and Procedure

The apparatus of Pilot Study 2 was used, with the addition of a fixation point in the middle of the display. The motion picture display of the horizon was employed. To restrict the subject's visual field, one eye was occluded, the other limited to a view slightly smaller than the boundaries of the display by means of an iris diaphragm in a goggles frame. Many trials were given similar in kind to those of previous pilot studies.

Results

The goggles had no effect on subject responses, which were overwhelmingly inappropriate (94%). The restriction did seem to add somewhat to the illusion of motion induced by the display.

Discussion

This only further confirms the strength of the tendency of the naive subject to respond inappropriately to the banking of a horizon-type display. The hypothesis that the absence of the surround would result in the display content becoming the frame of reference, and in consequence, appropriate responses becoming the natural ones, was not supported.

Pilot Study 5: Response to Pitch Motion

Pilot studies 1 through 4 all dealt with roll or banking motion. Most of the experimenters felt that the response to pitch would be much the same as to roll; the assumption was not tested until the roll experiments had been carried through.

Purpose

The purpose of the study was to test the response of naive subjects to a large articulated natural horizon display moving in the pitch plane, i.e., up and down.

Subjects

Two young adults with no piloting experience served as subjects.

Equipment and Procedure

Apparatus was the same as used in the previous experiment. Display motion, however, was achieved by moving a mirror which reflected the projector beam onto the back of the display.

The subject's joystick was adapted to operate a voltmeter to indicate fore-aft stick position. The subjects were trained as to the relation of the stick and the diving or climbing of the aircraft.

Each subject was given four series of eight trials, each series corresponding to the four series of roll presentations made to non-pilots in Pilot Study 3, as follows:

1. Beginning with a deviation which increases;
2. Beginning with no deviation, deviation starts in five seconds;
3. Beginning with a deviation that is decreasing, the task being to halt the movement at zero error; and
4. Stationary one-second exposures of deviations of four different amounts.

Results

Differences among the four series were slight, so that all could be lumped. Fifty-six of the total of sixty-four trials given to the two subjects evoked appropriate responses; the remaining eight responses were somewhat equivocal.

Discussion

This highly interesting result seems to show that pitch and roll behave differently in terms of direction of response. With identical displays, the pitch trials brought about a preponderance of appropriate responses; roll trials, a preponderance of inappropriate. The result, if confirmed by additional experimentation, is important to the understanding of the attitude display problem.

B. Experiment 1: Response to Pitch vs. Response to Roll

This experiment was designed to test rigorously the results appearing in Pilot Study 5.

Purpose

The purpose of the present experiment was to test the hypothesis that the natural control response of naive subjects to a large articulated horizon display moving in the pitch plane is appropriate, and that this is in contrast to the natural response of naive subjects to either banking motions presented on the same display, or to pitch motions on a small schematic horizon display.

Subjects

Twenty-four male high school seniors were employed as subjects.

Equipment

The control stand, pilot compartment, and display equipment of Pilot Study 2 were employed. The lower nine inches of the large (thirty-six inch) display were masked. Centered vertically in the mask a hole was cut, into which the tube face of a five-inch oscilloscope was placed. The 'scope was mounted at an angle, so its face was perpendicular to the subject's line of sight. A Kodachrome slide of the horizon was used to form the large display. By projecting through a dove prism held in a rotatable mount, the display as seen by the subject could be banked simply by turning the prism. To produce pitching motion, the display was projected onto a mirror and reflected onto the screen, the mirror angle being under the experimenter's control.

The oscilloscope was used to present a small "schematic" horizon display, consisting of a horizon line which could be moved up and down for pitch motions, and tilted right or left about the vertical axis of the 'scope for roll. The 'scope display was generated using standard analog computing components. The analog computer plus relay circuits were used to program trials with the 'scope display, the computer automatically introducing the display changes required by the experiment. The large display was operated manually. In both the large and small display, a relay triggered by the subject's control stick movement cut off the display and ended the trial. Movements of the stick in pitch and roll were shown to the experimenters via a second five-inch oscilloscope.

Procedure

There were four display conditions, since both the large articulated display and the oscilloscope display could move in either pitch or roll. Each condition was tested separately using three kinds of problems:

Problem a: Position plus motion. Three seconds of level flight, followed by a deviation (in roll or pitch);

Problem b: Motion only. The display showed a deviation at the outset, approaching zero at a constant rate, such that the display passed through zero four seconds after the trial began. The subject was required to respond at exactly this time.

Problem c: Position only. An initial unchanging deviation was displayed.

The three problems were equated approximately for amount and rate of change of deviations for the four display conditions.

There were four presentations of each of the three problems, two in each direction, or twelve trials for each display condition. These were presented in a randomized sequence. Since each subject was presented all four display conditions, there were a total of forty-eight trials per subject. To balance sequence effects, half the subjects, or twelve, received the large display conditions first and half the small. Each group of twelve was again divided, half receiving roll before pitch, the other half, pitch before roll. Table 4 shows the entire experimental sequence.

Table 4. Sequence of conditions for each subject in Experiment 1.

Groups of Subjects		Order of Presentation 1	2	3	4
Group I	1, 2, 3	roll, large	pitch, large	roll, small	pitch, small
	4, 5, 6			pitch, small	roll, small
	7, 8, 9	pitch, large	roll, large	roll, small	pitch, small
	10, 11, 12			pitch, small	roll, small
Group II	13, 14, 15	roll, small	pitch, small	roll, large	pitch, large
	16, 17, 18			pitch, large	roll, large
	19, 20, 21	pitch, small	roll, small	roll, large	pitch, large
	22, 23, 24			pitch, large	roll, large

Subjects were trained briefly in how to use the stick to affect the pitch and the roll of their aircraft, and practised following verbal commands from the experimenter. They were shown the displays, and were given typed instructions, which are reproduced on pages 57 and 58. Any questions about the instructions were answered. Usually there were no questions.

The subject scored one for each trial where his response was appropriate, zero where it was inappropriate. Total scores for a given kind of problem for each display condition ranged from zero to four for each subject.

Each subject was interviewed briefly at the completion of all the series. He was asked in the interview to identify quickly the position of his aircraft in relation to the horizon for two display sketches, one showing a roll, the other, a pitch deviation. His response to these sketches was scored as correct or incorrect.

Results

The effect of having roll first as compared to having pitch first was analyzed initially, because it seemed likely that there were no differences due to this sequence. If no differences were present, groups could be combined for further analysis. A Lindquist type one mixed analysis of variance

Table 5. Analysis of sequence effects in Experiment 1.

Source	Sums of Squares	d. f.	Variance Estimate	F	sig. level
Between S's	1179.67	23	51.29	2.34	.025
Between Groups	5.34	1	5.34	--	not sig.
Error between	1174.33	22	53.37		
Within S's	527.00	24	21.96		
Between Displays	216.77	1	216.77	15.6	.001
Interaction Groups & Displays	14.1	1	14.1		not sig.
Error within	304.89	22	13.86		
Total	1706.77	47			

INSTRUCTIONS TO SUBJECTS, EXPERIMENT 1

You are seated in the cockpit of an aircraft that is supposedly in flight. In front of you are two displays which will tell you whether your aircraft is banking to one side or another, i.e., rolling, or whether your aircraft is climbing or diving, i.e., pitching. The purpose of this experiment is to see how quickly you straighten up or level off your aircraft. Only one display showing either pitch or roll will be used in a particular series of trials. You will be informed which is to be used before the series begins. You control the motion of your aircraft by moving the joystick in front of you. You will not see the results of your control action. The display will be cut off before your control action has had time to take effect. A trial will end the moment you make a response.

Banking Control:

When you move the stick to the left while in straight or level flight, the aircraft will bank left (i.e., the left wing lowers and the right wing comes up). If your aircraft is banking right, moving your stick to the left will straighten you out.

When you move the stick to the right while in straight flight, the aircraft will bank right (the right wing lowers and the left wing comes up). If your aircraft is banking left, moving your stick to the right will straighten it out. Usually a pilot does not feel a bank to be as steep as it really is. Depending upon his speed and rate of turn, a pilot may feel that he is upright, or even banked slightly in the opposite direction to the true bank. He must, therefore, learn to rely on visual displays, and ignore bodily sensations of tilting, which may be deceptive.

Pitch Control:

When you push the stick forward while in straight or level flight, the nose of your plane will go down, i.e., plane dives. If your airplane is climbing, pushing your stick forward will level it. When you pull the stick back while in level flight, the nose of the plane will go up, i.e., plane climbs. If your airplane is diving, pulling the stick back will level it.

(continued)

At the beginning of each trial the Experimenter will say "Ready?" After your response "Ready," a trial will begin. A few seconds after a trial begins, the Experimenter will say "Now." Your job is to watch your display, then at the signal "Now" make your response by moving your joystick in the appropriate direction as quickly and spontaneously as possible.

Within a pitch or roll series of trials there will be three different kinds of problems:

1. At the beginning of a trial you may be in level flight, then go into a bank (or a dive or climb) at the moment the Experimenter says "Now." Your job is to move your stick to return your plane to level as soon after the "Now" that you can determine the motion of your plane.

2. Or your display may show that you are in a static position (a bank or climb or dive that doesn't change). Your job is to wait until the "Now" signal, then immediately make your response to return your plane to level flight.

3. Or your display may indicate that you are in a bank (or climb or dive) at the beginning of a trial, but coming out of it. Here your job at the "Now" signal is to move your stick in the direction that will stop the motion of the plane when it reaches level. If you make no control response, the motion of the plane would carry you beyond level into the opposite bank (or dive or climb).

This experiment involves low level flight. When your plane is level, its nose will be pointing at the midpoint of the horizon, the horizon will cut your display into two equal parts and will be parallel to the floor of this building.

Move the stick quickly and spontaneously. All you need to remember is that the plane will move in the direction you move the stick. Have you any questions?

was employed. (Lindquist, 1942.) The two groups, one having roll first, the other pitch, had been equated on the other experimental conditions. Results of the analysis of differences between these groups is summarized in Table 5. The table indicates that there are only insignificant differences between groups differing in sequence of display conditions. Differences between displays (roll vs. pitch) are highly significant, and those between subjects moderately so.

Since no significant sequence effects were found, data for all groups was lumped, and a four-way analysis of variance was carried out comparing displays (large vs. small), motions (pitch vs. roll), problems (a, b, and c), and subjects. This is summarized in Table 6. The fact that many of the main effects using the more stringent F ratio are not significant is due to the large interaction terms, which increase the denominator of this F ratio.

The mean scores for each of the four display conditions over all trials with all subjects were:

Display condition	Mean score
Large pitch	.649
Large roll	.174
Small pitch	.329
Small roll	.149

This indicates that responses were predominantly appropriate (65%) for the large pitch display, but predominantly inappropriate for the other three. Table 7 shows the significance of the differences between each pair of these mean scores. The "large pitch" mean score differs to a highly significant extent from the other three, of course.

The score obtained by each subject on each display condition could range from zero to twelve, the number of trials per condition. Distributions of these scores were highly abnormal, as is apparent from Table 8. The requirement for normality of distribution for analysis of variance and Fisher's "t" is obviously not met by this data. For this reason, the differences between the four display conditions as shown in Table 8 were again tested, this time using a simple test that made no assumption of normality of distribution or homogeneity of variance. Each of the six pairs of display conditions were cast into a fourfold chi-square table, grouping scores for each pair so as to obtain totals for rows as nearly equal as possible. Table 9 presents chi-square and the probability of chi-square for each pair. Even though this test

Table 6. Summary of four-way analysis of variance data for Experiment 1.

Source	Sums of Squares	d.f.	Var. Est.	F_1*	sig.	F_2**	sig.
D (Displays)	34.7	1	34.7	30.71	<.001	1.35	not sig
M (Motion)	122.7	1	122.7	108.58	<.001	4.8	not sig
P (Problems)	1.2	2	.6	not	sig		
S (Subjects)	188.8	23	8.2	7.26	<.001	3.28	<.01
D x M	25.7	1	25.7	22.74	<.001	10.3	<.01
D x P	1.7	2	.8	not	sig		
D x S	57.5	23	2.5	2.21	≐.01	1.00	not sig
M x P	1.8	2	.9	not	sig		
M x S	67.8	23	2.9	2.57	<.01	1.03	not sig
P x S	43.8	46	.96	not	sig		
D x M x P	2.7	2	1.35	1.19	not sig		
D x M x S	57.1	23	2.5	2.21	≐.01	2.21	≐.01
D x P x S	40.6	46	.88	not	sig		
M x P x S	34.2	46	.74	not	sig		
Residual	52.0	46	1.16				
Total	732.3	287					

*F_1: The usual F ratio tested against the Residual term.

**F_2: The most stringent F ratio that can be applied. It is achieved by the following steps:

1. Divide the variance estimate of the significant double interactions by a significant triple interaction variance estimate containing the same terms (in this case D x M, D x S, and M x S by D x M x S).

2. Divide the variance estimate of single terms by a significant double interaction variance estimate containing that term. (In this case D and M divided by D x M. S has no significant double interaction so it is divided by the significant triple interaction containing S which is D x M x S.

Table 7. Significance of the differences between means of four display conditions in Experiment 1, obtained by use of Fisher's "t" test.

Conditions	Significance Level
Large pitch vs. small roll	.001
Large pitch vs. large roll	.001
Large pitch vs. small pitch	.001
Small pitch vs. small roll	.001
Small pitch vs. large roll	.001
Large roll vs. small roll	not significant

Table 8. Number of subjects receiving each score in four display conditions in Experiment 1.

	Number of Subjects Having Each Score				
Score	Large Pitch	Small Pitch	Large Roll	Small Roll	Total
0	2	2	16	11	31
1	2	7	2	3	14
2	0	3	0	4	7
3	0	1	0	2	3
4	1	2	1	1	5
5	1	2	1	0	4
6	1	1	0	0	2
7	1	2	0	2	5
8	3	2	0	1	6
9	1	0	2	0	3
10	6	0	1	0	7
11	2	0	1	0	3
12	4	2	0	0	6
Total	24	24	24	24	96

Table 9. Chi-square and significance of chi-square for pairs of display conditions with distributions reduced to dichotomies at the cut-off points indicated. (Fourfold tables)

Display Conditions	Cut-off point between scores	Chi-square	Significance Level of Chi-square
Large pitch vs. small roll	3 and 4	16.75	$p = < .001$
Large pitch vs. large roll	4 and 5	14.08	$p = < .001$
Large pitch vs. small pitch	5 and 6	8.35	$p < .005$ ($< .01$)
*Small pitch vs. small roll	1 and 2	1.336	not sig*
Small pitch vs. large roll	1 and 2	5.42	$p < .02$
Large roll vs. small roll	0 and 1	1.354	not sig

* With cut-off between 0 and 1, Small pitch vs. small roll had a chi-square = 6.751, $p < .01$

throws away the distribution of data about the cutting point, high significance levels on four of the five pairs that were significant by "t" test were demonstrated. The fifth, small pitch vs. small roll, became significant only when the cut-off was changed to between zero and one, i.e., grouping subjects making 100% inappropriate responses vs. all others.

Results of the interview conducted at the close of each experimental session, to determine whether or not the subject could correctly determine the direction of aircraft pitch or roll from his display, were as follows:

5 subjects were correct on both pitch and roll;
10 subjects were correct on pitch only;
1 subject was correct on roll only; and
8 subjects were incorrect on both.

From the above it is apparent that fifteen subjects were correct on pitch, but only six were correct on roll. To see if interview results related to performance, the frequency of appropriate vs. inappropriate responses was totalled for the five subjects correctly identifying both pitch and roll, and for the remaining nineteen subjects. These results were cast in a fourfold table, and chi-square was computed. (Table 10) A similar table was made comparing the fifteen subjects correctly identifying pitch and the remaining nine, as is shown in Table 11. Both of these results are highly significant, demonstrating that subject performance was unquestionably related to ability to correctly infer vehicle attitude from the display.

Table 10. Fourfold contingency table of appropriate vs. inappropriate responses of subjects correctly identifying both pitch and roll diagrams vs. subjects incorrectly identifying one or both.

	Responses		
	Inappropriate	Appropriate	Total
Group I: 5 Subjects correctly identifying pitch and roll diagrams	96	144	240
Group II: 19 remaining Subjects	682	230	912
Total	778	374	1152

$x^2 = 103.24$, significant at $p < .001$ level of confidence

Table 11. Fourfold contingency table of appropriate vs. inappropriate responses of subjects correctly identifying pitch diagram vs. subjects failing to identify it correctly.

	Responses		
	Inappropriate	Appropriate	Total
Group I: 15 Subjects correctly identifying pitch diagram	426	294	720
Group II: 9 remaining Subjects	352	80	432
Total	778	374	1152

$x^2 = 60.306$, significant at the $p < .001$ level of confidence

Discussion

This experiment confirms the evidence of Pilot Study 5 that the response of naive subjects to pitch and to roll motions of a horizon display are different. The natural response with a small schematic display is to move the control "against" the motion of the display both in pitch and roll. Thus an "outside-in" display is desirable for ease of learning and minimum chance of reversal errors. This is well known. However, with a large articulated horizon display, the situation is confused. The natural response to roll motion is unchanged, so that an outside-in display is desirable for the same reasons as with the small display. The natural response to pitch motion, however, is reversed for this display. The natural response is such that an inside-out display would appear desirable.

The experimenters ran each other on the large display to get a better feel for the difference discovered. Their natural responses were in full accord with the findings. When the horizon rose, the feeling was that the plane was diving, and it was "natural" to pull back the stick. Conversely, when the horizon dropped, the feeling was of climbing, and the natural response to push the stick forward. These are appropriate responses. However, when the horizon tilted, there was no feeling of the plane banking in the opposite way, and the "natural" response was to oppose the horizon's motion. When the horizon dropped to the left, the "natural" response was to move the control in opposition to this movement, or to the right, and conversely when the horizon tilted in the opposite way. These are inappropriate responses.

As an addendum, the same large display was moved from side to side to simulate yaw movements, with the experimenters serving as subjects. It was agreed that the natural tendency was to make "appropriate" corrections, even more strongly, it appeared, than with pitch. Thus it is the roll motions which are atypical. A generalization might be, "It is easier for display content to become the frame of reference for translational motions than for rotational motions."

C. Experiment 2: Effect of Variations in Lags on Elimination of Reversal Errors, and on Tracking Accuracy in Vehicle Attitude Control

The general use of aircraft attitude indicators which move in the "wrong way" in terms of the response of a naive observer poses a training problem. In tracking experiments on other projects, Dunlap and Associates personnel have noted that reversal errors seemed more persistent with high-order slow responding systems than with low-order quick responding systems. If this could be established, it would make it possible to predict better in advance control systems in which reversal errors were likely to be a problem, and to train to counteract them. It also would suggest that a promising training method for such systems might be to begin on a simulator in which lags were very short, and reversals thus quickly eliminated, and to increase lags during training to resemble the real system.

Purpose

The primary purpose of this experiment was to test the hypothesis that reversal errors are more quickly eliminated when controlling a quick responding (short lag) vehicle than when controlling a slow responding (long lag) vehicle. The effect of variations in lags on training to increase accuracy of control was a secondary question to be considered.

Subjects

Twelve male high school seniors from the previous experiment served as subjects. Three groups of four were matched on the basis of their Experiment 1 responses.

Equipment and Procedure

The same cockpit, joystick, and five-inch oscilloscope display of roll were used as described in Experiment 1. In this experiment, however, the joystick fed into an analog computer, into one of two sets of simulated vehicle roll dynamics, the outputs of which fed into the display generating equipment to control vehicle roll. The vehicle dynamics consisted of a one-second exponential lag followed by an integration for the "short lag" system, and a five-second exponential lag followed by an integration for the "long lag" system. A forcing function generator also fed into the display generator, and was programmed to provide a disturbance consisting of a constant rate of change of the display in either direction, beginning five seconds after a problem started.

A six channel pen recorder recorded stick position, roll, rate of change of roll, forcing function, integrated absolute roll error (a score), and start and finish of each trial.

Subjects were divided into three groups of four subjects. Group I received training on the short lag system only; Group II, on the long lag system only; and Group III, on the long and short lag system.

All subjects received five training sessions under their assigned training condition. A training session was comprised of ten trials, each of which began with the aircraft in level flight, and after a few seconds the forcing function put the aircraft into a roll which the subject tried to correct. Fifteen seconds after the beginning of the forcing function, the trial ended. Training Group III, which received both long and short lag systems, was counter balanced. Two subjects received the long lag system in the first training session, short lag in Session 2, long lag in Session 3, short lag in Session 4, and long lag in Session 5. The other two subjects received the opposite, starting with the short lag system in Session 1. At the completion of five training sessions, all subjects were tested by ten trials on the long lag system.

Results

Table 2 on page 22 presents a summary of reversal error data for the two groups. "Reversal error" was defined as an inappropriate motion of the stick occurring immediately after the display was sent into a roll by the forcing function. These were therefore "initial reversals" only. No attempt was made to analyze reversals occurring at any other time during the trial.

Learning in the short lag group was immediate, so that by the end of the first training session reversals were already rare. It required two training sessions to bring the other two groups down to the level of reversals reached by the short lag group after one. Time per reversal follows the same pattern in that the fewer reversals made by the short lag group are corrected much more quickly in the first two sessions. From the third session onward, reversals occurred only rarely in any of the groups, however, and no differences between the groups are apparent.

The mixture of long and short lags in training, far from being an advantage, appeared to be a handicap in terms of number of reversals. Mean duration of reversals for this mixed training group was between the other two, as should be expected. However, the tracking performance of the mixed group was better by far than either of the other two groups, as is shown in Table 12. Despite their inferiority in reversal errors, the mixed training group learned to track out errors better than either of the others. It is interesting to note

Table 12. Means and standard deviations, and significance of differences between means of error scores on final test trial of groups of subjects trained under different lag conditions. (Error is in arbitrary units.)

Group	Mean	Standard Deviation	"t"	Significance of "t"
I. Short lag training	76.1	11.6		
II. Long lag training	78.6	14.3		
III. Mixed long and short lag training	65.6	17.8		
I vs. II			.84	Not significant
I vs. III			3.11	$< .005$
II vs. III			3.58	$< .001$

that the group trained on short lags had never experienced the long lag system until the test trial, yet they scored as well as did the long lag group, which had trained on the test trial system throughout.

Discussion

While this experiment amply confirms that reversals are eliminated more quickly for short lag systems than for long lag systems, it appears as if the experimental condition was too easy to show later reversals, which would have had greater significance. However, the use of short lag systems in combination with long apparently can result in substantially improved performance on the long lag system in terms of accuracy of control, as shown by reduced error scores. Therefore, the use of short lag systems in training has additional justification. The most desirable training method would be one which eliminated reversals as effectively as the short lag system, and trained for accuracy as well as the mixed system. A training program beginning with a short lag system only, and proceding later to mixed systems might well achieve this result.