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THREE LESSONS IN AVIATION RESEARCH

Edited by: Stanley N. Roscoe and Beverly H. Williges

Galileo and the Marketing Manager
Stanley N. Roscoe

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Beatrice E. Johnson and Alexander C. Williams, Jr.

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Foreword

The three lessons referred to in the title of this monograph are embodied in the master's theses of three people with whom I have been closely associated academically and professionally. Each, in different ways, is also closely identified with the late Alexander C. Williams, Jr., founder of the aviation psychology program at the University of Illinois:

Beatrice E. Johnson	Master of Arts in Psychology, 1950 University of Illinois at Urbana-Champaign Thesis advisor: Associate Professor Alexander C. Williams, Jr.
Gerald K. Slocum	Master of Science in Engineering, 1958 University of California at Los Angeles Thesis advisor: Associate Professor John Lyman
Lawrence A. Scanlan	Master of Arts in Psychology, 1971 University of Illinois at Urbana-Champaign Thesis advisor: Professor Stanley N. Roscoe

Miss Johnson, since 1953 Dr. Beatrice Johnson Matheny, was a fellow graduate student and coinvestigator under Williams at the Aviation Psychology Laboratory between 1947 and 1952, where she remained until 1954.

Mr. Slocum was an undergraduate engineering student at the University of Illinois who distinguished himself in my elementary psychology lecture course in 1952. When he graduated in 1955, he joined me at Hughes Aircraft Company where he worked closely with Williams for seven years and is now manager of the Display Systems and Human Factors Department.

Mr. Scanlan joined Hughes in 1967 as an electronics engineer and in 1969 was awarded a Howard Hughes Master's Fellowship to the University of Illinois. In 1970 he became the first recipient of the Alexander C. Williams, Jr., Doctoral Fellowship in engineering psychology, established by the Hughes Aerospace Group in 1962 but fallow for eight years for want of a suitable candidate.

Mrs. Matheny's thesis is presented in a form close to that in which she and Williams submitted it in 1949 as a report to the Special Devices Center, Office of Naval Research, under Contract N6ori-71, Task Order XVI. It is reproduced with the permission of the Naval Training Device Center, Orlando, Florida.

Beverly H. Williges and I have rewritten Mr. Slocum's thesis, restating the problem, shortening the literature review, and drawing additional implications from the results. It has been approved for publication in this form by Hughes Aircraft Company.

Mr. Scanlan's thesis appears essentially intact except for the deletion of 28 subsidiary figures and 72 pages of raw data. It was recently submitted in a similar form as an Aviation Research Laboratory report to the Air Force Office of Scientific Research under Task 1 of Contract F44620-70-C-0105, "Enhancement of Human Effectiveness in System Design, Training, and Operation," monitored by Dr. Glen Finch. The publication of this research has been approved by the United States Air Force and by Hughes Aircraft Company.

STANLEY N. ROSCOE
Editor

Galileo and the Marketing Manager

STANLEY N. ROSCOE

The three papers that constitute the substance of this monograph offer, by example, many lessons in the application of behavioral science methods to problems of aviation system design. Most of these will be left to the reader to discover in the text. Three will be pointed out in the commentary that follows.

THE INITIATION OF INQUIRY

"The most difficult portion of any inquiry is its initiation." So said F. S. C. Northrop (1947, p. 1) in opening his discussion of the exploits of Galileo in quest of laws governing the trajectories of cannon balls and the consequent demise of Aristotelian physics. "Inquiry starts only when something is unsatisfactory, when traditional beliefs are inadequate or in question, when the facts necessary to resolve one's uncertainties are not known, when the likely relevant hypotheses are not even imagined. What one has at the beginning of inquiry is merely the problem [p. 17]."

Considering that one starts with only the problem, it may seem surprising that the outcome of a formal experiment is almost never a surprise to the skilled investigator. In contrast, inexperienced investigators are forever collecting data that yield unexpected results. This difference is not accidental. The skilled investigator has learned his lessons, often at great expense and sorrow. For him, the purpose of the formal experiment is merely to demonstrate the reliability of an effect he has already discovered, to determine the exact shape of an observed functional relationship, or to establish the precise value of a threshold or a correlation.

How is it that the skilled investigator knows how his experiments will turn out while the unskilled frequently does not? The answer lies in how the skilled investigator initiates his inquiry. His first step is analytical and leads to the identification of all logically relevant variables. Evidently Galileo was able to analyze problems quickly, but for the garden-variety investigator, however experienced, the process typically is slow, particularly when a problem involves the behavior of human subjects, such as pilots flying airplanes.

Consistent with his analytical rigor, the careful investigator distrusts the facts upon which his analysis is based and resorts to inductive naturalistic observation, a euphemism for extensive informal pretesting. Pretesting is not to be confused with "pilot" experiments, little experiments usually involving a small subset of the experimental conditions ultimately to be investigated. The skilled investigator pretests his "main" experiment; he conducts a dress rehearsal, using as subjects himself, coworkers, and casual visitors, of which there are always many at any aviation research laboratory. He observes their performances naturalistically, records them objectively, scores them, plots them, and studies their reasonableness.

If nothing surprising turns up, if his instructions to subjects are always understood, and if his instrumentation for measuring performance is reliable, the investigator is ready to prove experimentally what he has already observed many times. But sometimes surprising things do turn up during initial stages of inquiry. The discovery that led to the experiment reported in the first of the three papers presented in this monograph was one such surprise; during pretesting, a variable previously overlooked turned out to have an effect on performance as important as the variables originally under investigation.

The problem stemmed from the fact that pilots may experience vertigo as a consequence of conflicting visual and vestibular cues related to changes in aircraft attitude. It was speculated, at the time, that the dominance of visual cues over the notoriously undependable vestibular cues was directly related to the degree of pictorial realism of visual displays. It was vigorously argued that, if visual displays were made sufficiently realistic, analogous to the pilot's contact view of the outside world on a clear day, disorientation due to conflicting vestibular cues would be eliminated.

To study this problem, a small room was mounted on a turntable, the angular acceleration of which could be controlled with a smoothness and precision that would have delighted Galileo. Displays having varying degrees of pictorial realism were presented through a window to a subject inside the cubicle. It was possible for the experimenter to cause all displays to indicate rotation in the same direction or in the opposite direction to that in which the subject was actually rotated.

From the outset of informal pretesting of the apparatus, it was apparent that even the most realistic visual display, a view of the surrounding laboratory through a clear window, could not consistently prevail over conflicting vestibular cues. The investigator informally tested everyone at the laboratory, and their responses were surprisingly and alarmingly inconsistent. Having exhausted the supply of laboratory personnel, she started asking flight instructors and students from the Institute of Aviation and casual visitors to serve as pretest subjects. Suddenly, as if by magic, pretest subjects started responding in accordance with original expectations.

A previously overlooked variable had been uncovered. The laboratory personnel all knew that the apparatus was designed to allow the experimenter to reverse the visually apparent motion and how this was done; the others did not know and, consequently, had no reason to doubt what they saw. By the time the investigator was ready to run her main experiment, *confidence in the displays* was a primary experimental variable (Johnson, 1950).

The other two papers in this monograph, each in its own way, also offer lessons in the initiation of inquiry. Both investigators were working under severe time limitations, and yet both spent most of their available time analyzing their problems, perfecting and pretesting their experimental equipment, their tasks, their procedures, and their performance measures. In each case, the actual data taking was accomplished in a very few days. For example, the 18 subjects in the experiment reported in the third paper detected 3,888 radar targets in only 17 days of formal data taking (Scanlan, 1971).

Despite the care taken by the investigator in the second study (Slocum, 1958), a serious methodological problem was neither apprehended nor corrected before formal data were collected. In developing meaningful performance measures for the task of locating and operating switches while flying an airplane, it became evident to the investigator that a measurable task requiring *primary* attention would be required so that the task of locating and operating switches could be relegated to its appropriate *secondary* role. This technique, now commonly referred to as side-task loading, had not previously been used in this way in aviation research.

Unfortunately, the instructions to the experimental subjects and the arrangement of the experimental situation failed to establish the desired primacy of the loading task, and as a consequence 5 of the 12 experimental subjects essentially ignored the loading task and concentrated their attention on what should have been the *secondary* task. Because of their partial defection, the results of the experiment were clouded, and the investigator gained some more invaluable experience in the initiation of inquiries.

THE PERVERSITY OF ANIMATE SUBJECTS

Galileo, through analysis, identified the logically relevant variables upon which the trajectory of a cannon ball, subject to the force of gravity, might depend. These were: the weight of the ball, the distance through which it falls, and the time during which it falls. By employing a gently inclined plane, thereby allowing him to chart the progress of balls of varying mass as a function of time following their release, Galileo was readily able to establish the relationship between the force applied and the motion of the ball: namely, force is proportional, not to distance or velocity, but to acceleration; the velocity of the ball is proportional to time; the distance it travels is proportional to the square of the time during which the force is applied. The Aristotelian definition of force was replaced by the Galilean definition, and both the scientific and the religious worlds were forced to make adjustments.

Once Galileo had hit upon the key variable, time, the verification of the crucial hypothesis was straightforward, because the objects of his experimentation, spherical balls, behaved with reasonable consistency. True, their acceleration down the inclined plane varied slightly, particularly when Galileo blew upon them, but these variations were relatively small and could readily be attributed to experimental error until it was remembered that the dispersion of cannon balls was greater when the wind was gusting than when the air was calm. It then became necessary to take proper physical account of the variable forces of friction.

Despite the added complexities of wind and weather, Galileo's difficulties in experimentation were trivial compared with those of the investigator seeking laws of aviation system design. Galileo dealt only with inanimate objects—balls, inclined planes, and clocks; the aviation researcher must deal with animate subjects—

pilots, flight instructors, students, and candidates for flight training. Animate behavior is far more variable than inanimate behavior because it is subject to biological, social, psychological, economic, and legal influences in addition to physical influences.

The perversity of animate subjects has, of necessity, whelped a remarkable degree of experimental sophistication in the behavioral sciences. Nevertheless, the practical business of doing meaningful research on real-world problems involving men and machines, particularly pilots and airplanes, is not widely understood. The problems encountered are seldom thought of as being fundamentally similar to those encountered in more traditional areas of behavioral research; indeed, they tend to be more dramatic, and their solution is frequently more expensive, but they have much in common.

Animate subjects exhibit remarkable variability in their performance of the complex tasks encountered in aviation. Not only do they vary one from another, but the same subject varies from time to time, typically improving rapidly while practicing any new task he may be called upon to perform. Transfer of training varies from one task to another, causing a subject's performance on one task to be affected differentially by the order in which he has been tested on other related tasks in the same experiment. Many investigators, failing to observe statistically significant differences among widely varying experimental conditions, erroneously conclude that the conditions are equivalent; *a difference that makes no difference is no difference*. Aside from the obvious fallacy of proving the null hypothesis, a practical as well as a theoretical impossibility, the effect of such a mistake is that investigators tend to stop investigating real problems.

A case in point is offered by the Slocum (1958) study reported in this monograph. The discriminability of shape-coded switch knobs had been studied vigorously following World War II. There was impressive anecdotal evidence that the meaningful shape coding of the landing gear and flap controls in the B-25 and other aircraft had virtually eliminated the inadvertent retraction of the landing gear following landing. However, further application of shape coding was stalled because no investigator had demonstrated a significant improvement in any critical switching operation attributable to the application of discriminably shaped switch knobs. Blunders such as retracting the landing gear following landing, although dramatic and expensive, occur infrequently during normal flight operations. Experiments designed to establish the statistical significance of blunder reduction in the cockpit attributable to the use of shape-coded switch knobs in routine flight operations might require years of data taking.

Fortunately the investigator in this particular study had the benefit of experience with problems of this type. He and his associates had struggled unsuccessfully for months attempting to demonstrate a statistically significant improvement in radar target detection with a new display their company had developed. Despite the evident ease of detecting simulated targets on the new display compared with the difficulty of detecting the same targets on the type of display used in all airborne systems manufactured by that company, the ranges at which targets were first detected were virtually identical for both displays.

Everyone who visited the laboratory was greatly impressed by the new display, and its inventor received an on-the-spot raise of $25.00 per week when the general manager first saw it; but, strictly on performance, there was no justification for spending millions to replace the old with the new. The manager of marketing was beside himself and often beside the investigator. Something had to be wrong with the experiments; some crucial variable was missing; surely some factor present in the operational flight situation had been omitted from the simulation. The marketing manager needed an answer or a miracle.

Fortunately the investigator's department manager recalled an even earlier relevant experience. Initially he had been unable to demonstrate what later turned out to be a big and reliable difference between two groups of displays used in the control of aircraft altitude (Williams, 1947). In that case, the initially equivalent levels of pilot performance, with display systems presenting vastly different information, became widely separated when the complexity and difficulty of the flight tasks were abruptly increased.

The department manager suggested that the detection of weak target returns in a background of radar noise might, perhaps, be too easy for a subject having no other tasks to perform. It is a matter of previously unpublished scientific record that within a few days, subjects were making significantly fewer errors and responding with significantly shorter latencies on a battery of operationally meaningful side tasks while using the new display, although they continued to detect targets at equal ranges on both displays. The new display was eventually adopted and retrofitted into hundreds of airplanes, and the marketing manager's office now has pecan paneling and a carpet.

With the benefit of this fresh experience, the investigator set about to create an experimental task situation in which the normal incidence of blunder in cockpit switching operations would be sufficiently high to allow the blunder-preventing potential of meaningfully shape-coded switch knobs to rise above the variability of animate subjects. During the initiation of inquiry, the investigator realized that his problem would not be solved merely by adding a side task that would reveal differences in a subject's residual attention while giving primary attention to switching tasks. That would not prove that switching blunders could be reduced. To do so would require a complex task situation in which the loading task was primary and the switching task secondary, thereby casting the bulk of the between-condition variability into the incidence of switching blunders.

The fact that the investigator was less than completely successful in creating the desired task situation, as evidenced by the unexpected behavior of five subjects during formal testing, takes some of the shine off the experiment, but it detracts little from the evident methodological wisdom of the investigator. His experimental technique demonstrated at an early date that side-task loading, in addition to (1) forcing differences in performances among conditions through elevated workload pressure and (2) providing a sensitive measure of what we now call residual attention, can be used for another purpose, (3) the manipulation of priorities in a task hierarchy.

BEHAVIORAL SOLUTIONS TO ENGINEERING PROBLEMS

Engineering problems have traditionally been thought of in terms of physical solutions. Galileo, fortunately for the physical sciences, chose to study the trajectories of cannon balls; he might well have chosen to study the behavior of the soldiers that aimed the cannons, for they provided by far the greatest contribution to the dispersion of renaissance projectiles. Had he done so, his initial inquiry into the perversity of animate subjects would surely have led him rapidly to the hypothesis that the dispersion of cannon balls can be reduced more by designing the cannon to match the soldier than by training the soldier to aim a badly designed cannon.

Despite his analytical and experimental genius, Galileo would have had great difficulty testing the hypothesis just stated because, in his time, the sophisticated experimental designs and methods of statistical analysis developed by behavioral scientists were separated from him by three centuries. Fortunately, they were available and well known to the young electronics engineer who was the investigator in the third study presented in this monograph (Scanlan, 1971).

His experiment, completed in 17 days after two months of analysis, experiment planning, equipment development and checkout, and subject pretesting, demonstrated a behavioral solution to a difficult engineering problem. His results show how engineering design variables can be interactively manipulated to achieve a dramatic improvement in the performance of certain types of radar systems, with potentially large cost savings, by taking advantage of a remarkable property of the human perceptual system.

However impressive his initial findings may be to the marketing manager, they almost certainly are but the visible portion of a scientific iceberg. Just as the implications of Galileo's solution to his initial problem reached far beyond the cannon ball, investigation of visual time-compression phenomena may lead to the explanation of the perplexing spatial and temporal integration processes of the human brain. It may also lead to engineering applications unimagined by Galileo or, for that matter, by the marketing manager. Experiments of this kind are basic to the extent that their results are generalizable to a wide range of applications, as were Galileo's cannon ball experiments.

The acceleration with which the rest of this scientific iceberg is forced to the surface will depend upon the imagination with which investigators follow the step-by-step process of scientific inquiry summarily stated by Northrop (1947, p. 28):

> First, *the discovery by analysis of the basic theoretical root of the problem;*
> second, *the selection of the simplest phenomenon exhibiting the factors involved in the difficulty;*
> third, *the inductive observation of these relevant factors;*
> fourth, *the projection of relevant hypotheses suggested by these relevant facts;*
> fifth, *the deduction of logical consequences from each hypothesis, thereby permitting it to be put to an experimental test;*

sixth, *the clarification of one's initial problem in the light of the verified hypothesis;* and
seventh, *the generalization of one's solution by means of a pursuit of the logical implications of the new concepts and theory with respect to other subject matter and applications.*

• • •

If any moral is to be found in these lessons, it is this: Given the choice of being the principal investigator or the marketing manager, go for the pecan paneling and carpet.

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Obedience to Rotation-Indicating Visual Displays as a Function of Confidence in the Displays

BEATRICE E. JOHNSON AND ALEXANDER C. WILLIAMS, JR.

INTRODUCTION

The phenomenon of disequilibrium is a relatively frequent occurrence in everyday life. Certainly almost everyone has experienced the sensation of movement when the car in which he is riding is stopped and an adjacent car is drifting. Many movement illusions are fleeting and harmless, but there are some that can and do lead to disaster. Perhaps the most important of these is the vertigo experienced by an aviator in flight. It is the purpose of this paper to investigate the relationship between the confidence a pilot has in his visual display and his susceptibility to disorientation.

Aviator's vertigo is a form of disorientation resulting from accelerative and decelerative forces encountered while piloting an airplane. Because of its frequent occurrence and potential for disaster, it is one of the most serious forms of disturbed equilibrium based upon psycho-physiological causes.

McFarland (1946) classified the disorientation a pilot may experience into three types. These are: (1) the pilot makes no effort to correct the discrepancy between his illusion and the actual attitude of the aircraft because he is unaware that he is disoriented; (2) the pilot is unable to overcome the illusion and correct for the error in orientation because the erroneous cues are so strong; and (3) the pilot feels disoriented, although he maintains correct orientation by relying on the information presented by the instruments in the cockpit.

Among the sources of information that contribute to a pilot's maintenance of his equilibrium are visual cues, sensations from the vestibular mechanism, kinesthetic cues, tactual and organic sensations, and cues from motor adjustments. During contact flight, visual cues from the surrounding terrain serve as fixed reference points and enable the pilot to maintain correct orientation. However, during night and instrument flight, when visual cues are not available or are reduced, other cues, such as vestibular sensations, become of prime importance. These secondary cues may yield completely erroneous information to which the pilot may respond.

The interest and research in disorientation can be traced back to Darwin in 1801 (Boring, 1942, p. 535). More recently, accidents in flying have led to an intensification of research into the critical factors in disorientation. These factors appear to be numerous, and many phases of the problem have never been investigated.

The importance of vision as a factor in body equilibrium has been well established. The use of visual cues may either facilitate orientation or reinforce body disequilibrium. A pilot may react to illusory phenomena with as much certainty as he would to real movement. McFarland (1946) gives the excellent example of disorientation in which a pilot uses a gently sloping cloud bank as an objective point of reference. The angular accelerations needed to keep the aircraft's wings parallel with the cloud bank may be so slight that they are unnoticed by the pilot. The resulting disorientation could be initially confusing and eventually disasterous if the pilot attempts to maintain a desired heading while holding the airplane's wings parallel to the sloping cloud tops.

Visual illusions experienced during night flying are especially distressing and dangerous. The oculogyral illusion is the most important of these visual phenomena. The oculogyral illusion may be produced when a subject is rotated while observing a light that maintains a constant position in his visual field. During acceleration, the light appears to move in the direction of rotation. With constant-speed rotation the light comes to rest, may then oscillate slightly, and finally becomes motionless. During deceleration the light seems to move in the direction opposite to that of the previous rotation. During night flying the visual field may appear to rotate in the manner of the light.

When visual cues are restricted, the threshold of movement illusions seems to change. Using pigeons as subjects, Mowrer (1935) found that less acceleration was needed to produce the nystagmic reflex when visual cues were excluded. Graybiel, Clark, MacCorquodale, and Hupp (1946) confirmed Mowrer's results using human subjects. When the subjects were rotated in the dark with minimal visual cues, the oculogyral illusion was reported. The illusion was not reported when the rotation occurred in a well-lighted room.

Because of the importance of vision to spatial orientation, many researchers have examined particular factors of the visual stimuli and their influence on bodily orientation. Travis (1945) reported that performance in spatial orientation improves when more detail is included in the visual field. Degree of bank also influences the frequency of visual illusions. Clark, Graybiel, and MacCorquodale (1948) reported that the probability of occurrence of the oculogyral illusion in a Link trainer increases as bank angle increases from 10 degrees to 60 degrees.

An interesting trend is observed in reviewing the experiments on visual apprehension of movement during vestibular stimulation. Most researchers report a considerable variability in the responses obtained. In fact, variability of rotational response seems to be the rule, not the exception (Clark, Graybiel, and MacCorquodale, 1948; Graybiel, Clark, MacCorquodale, and Hupp, 1946; Gurnee, 1931; and McFarland, 1946).

Unpublished preliminary studies at the Aviation Psychology Laboratory of the University of Illinois suggest that the reason some pilots are subject to vertigo under conditions in which others are not may be related to the extent to which different pilots rely on the information presented by their flight instruments. In these studies, each subject was presented various visual displays through an aperture in the wall in front of him while they were rotated in a small cubicle mounted on a turntable. The displays provided their only visual cues of motion.

Despite identical experimental conditions for all, some subjects showed no directional disorientation; others experienced directional disorientation throughout most of the trials. Disoriented subjects did not report the same illusion consistently within a given trial or between trials. The subjects who had not become disoriented reported that they relied on the movement cues provided by the visual displays, whereas the disoriented subjects disregarded the visual cues when they contradicted other sensations. Disoriented subjects reported they believed the experimenter was trying to deceive them.

The results of these experiments suggest that some factor or factors other than the external stimuli were operating and that a pilot's tendency toward disorientation may depend upon his lack of confidence in his visual displays.

METHOD

To test the relationship between confidence in a visual display and disorientation, it was essential to establish in the subjects two opposing levels of confidence, one of complete confidence in the visual display and the other of little or no confidence in the visual display. Under the condition of *high confidence,* a subject had no reason to doubt the veracity of the information presented visually. Under the condition of *low confidence,* a subject was shown how the displays could be manipulated to produce misleading information.

Equipment

The experimental apparatus included a plywood cubicle mounted on a circular rotating turntable powered by a one-horsepower reversible motor. A chair with a headrest restricting left-right head movement was mounted in the center of the cubicle. A one-way mirror, inset into the front wall of the cubicle, allowed a subject to see out when the light outside the cubicle was greater than that within.

Subjects used an airplane-type control stick that projected from the front wall of the cubicle. This control was limited to right-left movement and was used by a subject to indicate his perceived direction of rotation.

On the outside of the cubicle, a large Pancro mirror could be adjusted to project at a 45-degree angle from the front wall. The first-surface mirror was used to avoid the double images inherent in a regular mirror. When placed in the 45-degree position, the mirror caused the external view from the cubicle to be bilaterally reversed as shown in Exhibit 1.

An artificial visual display, painted on a continuous belt, could be moved past the aperture in the front wall of the cubicle by means of two modified kymograph drums as shown in Exhibit 2. The display was powered through a reversible connection with the drive shaft of the turntable, thereby allowing it to move in either direction relative to the direction of rotation of the cubicle. This display, simulating earth, sky, and horizon as viewed from the air, was made to look very realistic but could not be mistaken for the actual surroundings. To increase the realism of the painted display, no roads or rivers were represented as being either vertical or horizontal as viewed by a subject. The landscape faded out in the distance by the blending of mountaintops with clouds.

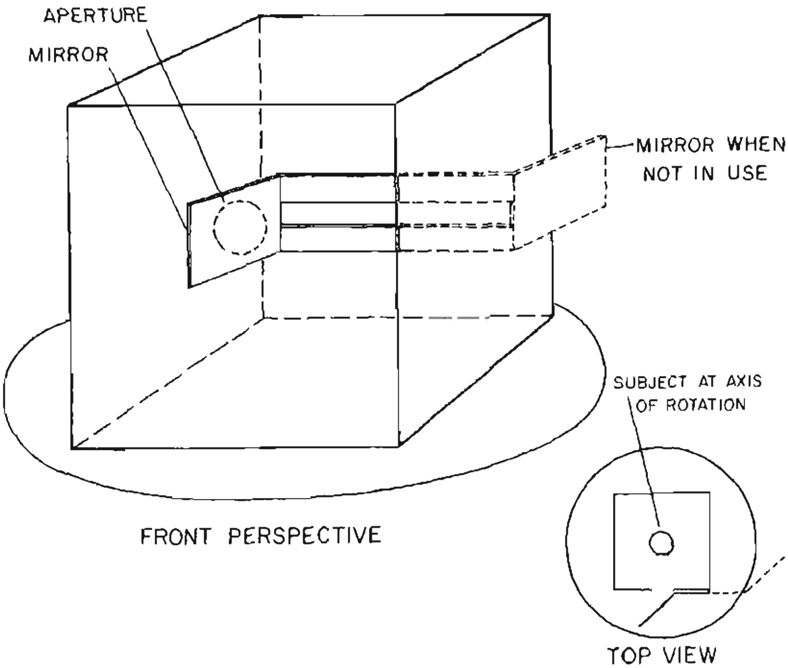

Exhibit 1. Apparatus showing location of the mirror.

Experimental Conditions

Two levels of realism of visual display were used. One was the restricted view of the surrounding laboratory. It was thought that this type of visual display should produce a high level of confidence because of its high degree of realism. The artificial panoramic display painted on the continuous belt was designed to afford somewhat less realistic visual cues.

The visual information in the restricted view of the room or the painted display was presented either directly or bilaterally reversed. The view of the room was bilaterally reversed by placing the mirror at a 45-degree angle to a subject's line of sight as shown in Exhibit 1. The panoramic display was reversed by changing the drive-shaft connection so that the relative motion of the artificial display was in the same direction rather than in the direction opposite to the angular rotation of the cubicle. Thus, in both bilaterally reversed conditions, apparent movement was in the direction opposite to the actual movement, thereby yielding contradictory visual and vestibular cues.

When the variables of display realism and direction of apparent

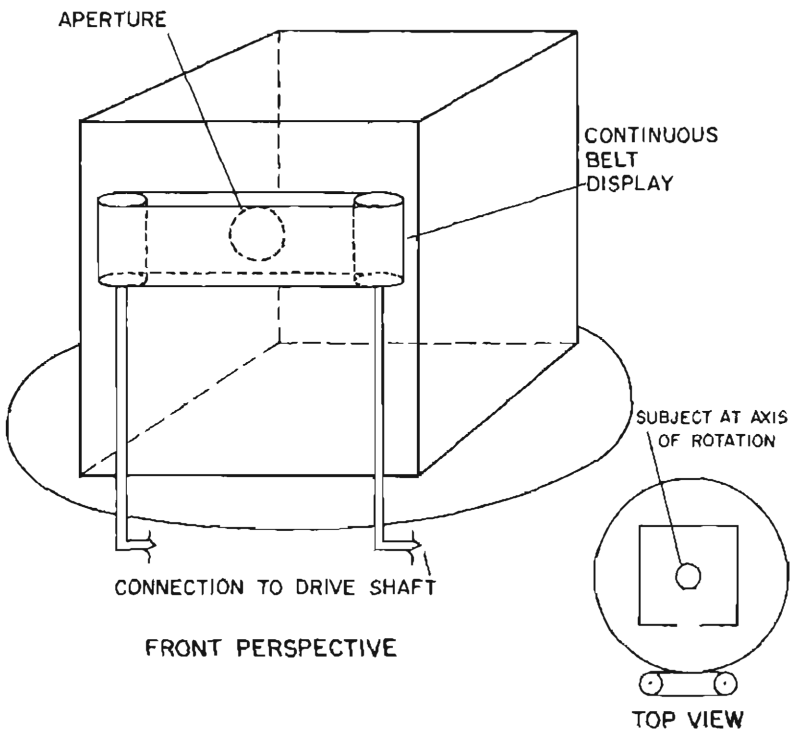

Exhibit 2. Apparatus showing the artificial display in position.

rotation were combined, four experimental conditions resulted. Exhibit 3 summarizes these four conditions.

Subjects

Twenty male University of Illinois students enrolled in the flight curriculum at the Institute of Aviation were used as subjects. All were naive with respect to the equipment and the purpose of the experiment.

Procedure

Before entering the laboratory, each subject was given instructions designed to direct his attention away from the true purpose of the experiment—the investigation of his perception of the direction of rotation. The experimenter told each subject that the study was designed to determine how accurately and at what points a person is able to perceive positive and negative angular accelerations.

Exhibit 3. Experimental conditions categorized according to direction of apparent rotation and level of realism.

Level of Realism	Apparent Rotation	
	Correct Direction	Reversed Direction
Actual Surroundings	Direct View of Room	Reversed View of Room
Artificial Display	Direct Panoramic View	Reversed Panoramic View

Upon entering the laboratory, each subject was blindfolded. The blindfold was removed when he was seated in the chair inside the cubicle. At this point the subject was told to move the control stick in the appropriate direction whenever he felt acceleration or deceleration. He was also told that the pressure on the control stick should remain steady under a constant speed. When the cubicle was stopped, the control stick was to be placed in its neutral position.

One preexperimental trial using the direct view of the room was given to insure that the instructions had been understood. Each subject was then run through a series of trials termed the *high confidence level* trials. These trials consisted of rotating once to the right and once to the left in each of the four experimental conditions. The presentation order of experimental conditions and of the direction of rotation was randomized.

Following this series of trials, each subject was told that the actual purpose of the study was to measure how accurately a person perceives direction of rotation, not acceleration. To destroy confidence in the visual information presented, a subject was allowed to inspect the equipment. The use of the Pancro mirror and the reversible drive of the artificial display was demonstrated. Following this inspection, a subject was again run through a series of trials using a different random order. These trials were termed *low confidence level* trials.

Because the experiment was designed to determine the role of confidence in information presented visually, a response was recorded as correct or positive when it corresponded to the apparent direction of rotation as presented visually regardless of the actual direction of rotation of the turntable. If the response deviated in any way from that appropriate to the visual information presented, it was recorded as incorrect or negative. Thus, if a subject became confused and moved the control stick to a neutral position prematurely or to the incorrect side, the whole trial was considered to be incorrect. This method of scoring was selected on the premise that, if a subject had complete confidence in the visual cues, he should not become confused at all during the trial.

RESULTS AND DISCUSSION

An analysis of the number of positive responses in each experimental condition was performed to determine whether a loss of confidence in the visual displays altered response to rotation. A second analysis was made to determine whether responses differed among the four experimental conditions. Originally, the effects of two variables were examined: the realism of the visual display and the apparent direction of rotation. Results from these comparisons led to a further analysis in which the experimental conditions were categorized according to whether there was agreement or disagreement between visual and vestibular cues.

Effect of Loss of Confidence in the Visual Display

Exhibit 4 shows the results of the experimental trials expressed in terms of the percentage of positive responses in each of the four experimental conditions at the two levels of confidence. Two relationships are apparent from these results. First, there was a noticeable shift in the percentages of positive and negative responses for each experimental condition from one level of confidence to another. Second, the percentages of positive and negative responses within each level of confidence varied among the four experimental conditions.

The shift in positive responses related to the change in level of confidence is central to the purpose of the study. The Chi-square test was used to analyze the differences between the responses at

Exhibit 4. Percentage of positive responses for each experimental condition at the two levels of confidence.

Experimental Condition	Level of Confidence	
	High	Low
Direct View of Room	100%	78%
Reversed View of Room	75%	33%
Direct Panoramic View	60%	28%
Reversed Panoramic View	50%	8%

the two levels of confidence. All four Chi-square values were significant ($p < .01$). The variation in responses between the two levels of confidence may be attributed to a shift in the subjects' confidence in what they saw. Thus, destroying a pilot's confidence in what he sees can make a difference in whether he responds on the basis of visual cues or other information, presumably vestibular and kinesthetic cues.

The importance of confidence in visual information is illustrated by two results. First, when a subject had a high level of confidence in what he saw, he responded in accord with the visually presented information more than half the time even when the information contradicted the direction of actual rotation. In addition, the subject's confidence in the direct view of his surroundings was destroyed to such an extent that performances in the high and low confidence levels were significantly different. This loss of confidence was achieved without changing the actual visual surroundings or the vestibular and kinesthetic stimulation in any way.

Differences among the Four Experimental Conditions

The order of the four experimental conditions in terms of positive responses did not change from one level of confidence to another. In both cases, the direct view of the room resulted in the most positive responses, the bilaterally reversed image of room was next, the direct panoramic view ranked third, and the bilaterally reversed panoramic view was last. The Chi-square test was used to compare differences in positive and negative responses for the four experimental conditions under both levels of confidence. The results of these tests are summarized in Exhibit 5.

At the high confidence level the direct view of the room was the only experimental condition that was significantly different from every other condition at the .01 probability level. However, the bilaterally reversed image of the room differed significantly from the bilaterally reversed panoramic view at the .05 level. There was not a significant difference between the bilaterally reversed image of the room and the direct panoramic view or between the direct and bilaterally reversed panoramic views.

In spite of the attempt to establish an equal amount of confidence in the correctness of visually presented rotational information at the high confidence level, the results indicate that the subjects responded differently to each experimental condition. These

Exhibit 5. Chi-square values for the differences in frequencies of positive responses for the experimental conditions at the two confidence levels.

Experimental Condition	Reversed Panoramic View	Direct Panoramic View	Reversed View of Room
High Confidence Level			
Direct View of Room	.26.6**	20.0**	11.4**
Reversed View of Room	5.4*	2.0	
Direct Panoramic View	0.8		
Low Confidence Level			
Direct View of Room	40.0**	20.2**	16.4**
Reversed View of Room	7.6**	0.2	
Direct Panoramic View	5.6*		

Note: The experimental conditions are ranked from high to low on the basis of number of positive responses.

* $p < .05$
** $p < .01$

differential responses to the various experimental conditions were also found in the low confidence level. This would suggest that there were inherent differences in the credibility of the information presented by the four displays.

Two factors may have contributed to these differences among the experimental conditions: the realism, or quality, of the display and the agreement of the rotational orientation of the display with the actual direction of rotation. The question to be answered is whether these differences were great enough to alter significantly the subjects' responses to the various experimental conditions. In other words, under what conditions and to what degree did the subjects accept the information provided by the display?

Quality of the visual display. To answer the foregoing question, two comparisons dealing with the quality of the display were made. First, the direct view of the room was compared with the direct panoramic view. This yielded a measure of display quality with both displays correctly oriented for the actual direction of rotation. Similarly, the bilaterally reversed image of the room and the bilaterally reversed panoramic view (both incorrectly oriented for the actual direction of rotation) were compared.

The Chi-square values for these comparisons are given in Exhibit 6. In both cases the experimental conditions that presented views of the actual surroundings were significantly superior in terms of positive responses to those that presented artificial displays. These results suggest that the subjects had more confidence in the information provided by their actual surroundings than by an artificial display. The more realistic the display, the more consistently the subjects responded in accordance with the information presented. Possibly this relationship applies to visual displays in general.

Exhibit 6. Chi-square values for the comparisons of the realism of the displays at each level of confidence.

Comparison	Level of Confidence	
	High	Low
Direct View of Room with Direct Panoramic View	20.0**	20.2**
Reversed View of Room with Reversed Panoramic View	5.4*	7.6*

* $p < .05$
** $p < .01$

Apparent direction of movement of the visual display. A second set of comparisons was concerned with the agreement or disagreement of the apparent direction of movement of the visual display and the actual direction of rotation. The direct view of the room and the bilaterally reversed image of the room were compared. Both were displays of the actual surroundings, but one was correctly oriented and one incorrectly oriented for the actual direction of rotation. In the same manner, the direct panoramic view and the bilaterally reversed panoramic view were compared to yield similar information about artificial displays.

The Chi-square values for these comparisons are given in Exhibit 7. In the analysis of the results, the actual surroundings correctly oriented were superior to the actual surroundings incorrectly oriented. However, the responses to the direct and bilaterally reversed panoramic views differed significantly only at the low confidence level. This would suggest that the apparent direction of movement of the artificial displays was not a significant factor at the high confidence level.

The question arises as to why there should have been this exception. Possibly the preceding comparisons are not justified, because the two conditions used in each comparison differed not only in the direction of movement of the display with respect to the turn-

Exhibit 7. Chi-square values for the comparisons of the apparent direction of movement of the displays at each level of confidence.

Comparison	Level of Confidence	
	High	Low
Direct View of Room with Reversed View of Room	11.4**	16.4**
Direct Panoramic View with Reversed Panoramic View	0.8	5.6*

* $p < .05$
** $p < .01$

table but also in cue agreement between the visual and vestibular senses.

Analysis of cue agreement. If each trial is broken down into its three component parts—acceleration, constant-speed rotation, and deceleration—it is possible to isolate and categorize the visual and vestibular cues as to agreement or disagreement.

During acceleration the vestibular and visual cues agreed only under the two conditions of the direct view of the room and the direct panoramic view. In the other two conditions, the two sources of information disagreed as to the direction of rotation during acceleration.

During constant-speed rotation, visual and vestibular cues always disagreed because the visual cues showed movement while the vestibular mechanism provided no information whatever. The disagreement was over the fact of rotation, not its direction.

During deceleration there was always a disagreement of cues, because the visual cues showed that the turntable was stopping while the vestibular cues gave the after-rotation illusion. The disagreement was again one of the fact of rotation, but it differed from that during constant speed in that both the visual and vestibular cues were active during deceleration. During constant-speed rotation only the visual cues were active.

Exhibit 8 categorizes positive responses in each experimental condition according to whether visual and vestibular cues agreed or disagreed. Because only the visual cues were active during constant-speed rotation, responses during this part of the trials were not included in the analysis.

Several questions arise from examining Exhibit 8, each of which

Exhibit 8. Raw score distribution of positive responses categorized according to agreement or disagreement of visual and vestibular cues.

Experimental Condition	High Confidence Level		Low Confidence Level	
	Agreement	Disagreement	Agreement	Disagreement
Realistic Displays				
Direct View of Room	40 (acc.)	40 (dec.)	37 (acc.)	34 (dec.)
Reversed View of Room		36 (acc.)		17 (acc.)
		33 (dec.)		30 (dec.)
Artificial Displays				
Direct Panoramic View	38 (acc.)	25 (dec.)	32 (acc.)	12 (dec.)
Reversed Panoramic View		20 (acc.)		5 (acc.)
		24 (dec.)		12 (dec.)

can be answered only tentatively by the results of the present study. The first question is whether the quality of the display is an important factor in determining a response when the visual and vestibular cues agree. There were only two instances of cue agreement and a difference in the quality of the displays. These conditions were the direct view of the room during acceleration and the direct panoramic view during acceleration. The Chi-square values comparing these two conditions were 2.0 (high confidence level) and 2.6 (low confidence level). Neither value was significant. The quality of the visual display may be relatively unimportant when visual and vestibular cues agree.

Conversely, a second question concerns whether or not the quality of visual displays is important when visual and vestibular cues do not agree. To answer this question the responses to the two different display qualities made under cue disagreement were compared at the high confidence level. The number of positive responses associated with realistic display quality were 40, 36, and 33; the numbers associated with artificial quality were 25, 20, and 24. There was no overlap between the two categories, and the difference between the lowest value of realistic quality (33) and the highest value of artificial quality (25) was significant ($p < .05$). Because this comparison was significant, all other comparisons would also be significant. In the low confidence level, the trend was again evident: the frequency of positive responses to realistic quality (34, 17, and 30) did not overlap the frequency of positive responses to artificial quality (12, 5, and 12). These results support the idea that the quality of a visual display is important when visual and vestibular cues disagree.

It is interesting to note that the responses to the direct view of the room did not differ whether cues agreed or disagreed under either the high or low confidence levels. Thus, for a display of realistic quality, cue disagreement may not be an important factor in determining the response.

The results in Exhibit 8 also indicate that responses made under conditions of disagreement of cues differed significantly under acceleration and deceleration only at the low confidence level. Thus, one effect of loss of confidence in the visual information was to distinguish between the type of cue disagreement during acceleration and deceleration.

A final hypothesis which arises from the data in Exhibit 8 is that the loss of confidence in a visual display is more important with artificial displays than with realistic displays. Progressing from the artificial displays to the realistic displays, the differences between the responses made at the high confidence level and those made at the low confidence level become smaller.

IMPLICATIONS

Overall, the results of this study have implications for both pilot training and aircraft instrument design. Student pilots should be made aware of the normal conflicts of visual and vestibular cues which do arise in the perception of aircraft motion and be instructed to have confidence in their instruments. In considering instrument design, the results indicate that the more realistic a visual display can be made, the more effective it will be.

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Meaningful Shape Coding for Aircraft Switch Knobs

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INTRODUCTION

In the spring of 1945, a C-46 cargo plane touched down on the coral runway at Peleliu Island and, as it rolled toward a stop, gently settled lower and lower until its belly met the concrete-hard surface with a shower of sparks and, finally, an explosion and flames. The copilot had inadvertently retracted the landing gear instead of the flaps. On the C-46, the levers used to operate the gear and flaps are located side by side and have handles of approximately the same size and shape.

Many similar accidents have occurred because a pilot failed to identify the proper control. In a survey of pilot error experiences, Fitts and Jones (1947) reported that of the 460 error experiences recounted to them, approximately 50 percent resulted from the substitution of one control for another. One possible solution to this problem of misidentification might be to color code the various control knobs in the cockpit. However, because a pilot often needs to operate a side-console switch or other remotely located control while watching his flight instruments or radar display, a visual identification code is of limited use.

Shape Coding

An alternative solution is to shape code various control knobs. A tire-shaped knob is now used to raise or lower the wheels of aircraft, and a wedge-shaped knob is used to control the flaps. Meaningful shape coding has virtually eliminated accidents caused by the confusion of the landing gear and flap controls. Safe aircraft operation requires that many controls be operated quickly with a minimum of visual reference, and shape coding of control knobs permits rapid and accurate discrimination by tactual cues alone.

Researchers have attempted to identify a comprehensive set of easily discriminable knob shapes to be used in aircraft (Hunt and Craig, 1954; Jenkins, 1946a; 1946b; Jones, 1947). Their findings have differed on many shapes, but there is general agreement that certain geometric forms, such as the triangle, the rectangle, and the sphere, and certain letters, such as I, L, and U, can be readily recognized by feel alone.

Limitations of Previous Research

Unfortunately many studies of knob shape coding have not used procedures that parallel the actual operation of an aircraft. For example, many studies have used a paired-comparison technique to evaluate shapes (Brennan and Morant, 1950; Jenkins, 1946a; 1946b; Jones, 1947; Whittingham, 1948). A subject feels one shape and then another and reports whether they are the same or different. This information has been used to recommend easily recognizable knob shapes. Incongruously, when these coded controls are actually used, the operator makes an absolute rather than a relative judgment. A more realistic experimental procedure would require subjects to make an absolute judgment as they would in the actual operation of an aircraft.

Another factor that has been overlooked in knob shape-coding experiments is the importance of speed as well as accuracy in selecting the proper control. A delay of a few milliseconds can be critical in aircraft operation. The studies by Austin and Sleight (1952a; 1952b) are among the few that actually measured discrimination time.

An additional real-world problem that has often been neglected in research on shape coding is the need for a measure of the time required to manipulate knobs having different shapes. Churchill (1955) found significant differences in the time required to manipulate each of eight previously recommended knob shapes. Obviously, a knob that can be identified and manipulated quickly is to be preferred over a knob that is equally discriminable but requires significantly more manipulation time.

Previous studies have considered the tactual discrimination problem to be the only task occupying the subject's attention (Hunt and Craig, 1954; Jenkins, 1946a; 1946b). A pilot, however, could be busy with another task, such as tracking a target or navigating, while simultaneously being required to select the proper knob for adjustment. If a knob coding system requires the total attention of the operator, it is of little value. Because the purpose of shape coding is to allow a pilot to complete one task visually while he tactually locates and manipulates a coded control, studies using the discrimination task alone could be misleading. Subjects should be required to perform another task simultaneously with knob identification to provide a measure of the amount of attention available during knob identification that could be diverted to another task.

Associating Shapes with Functions

Despite these procedural difficulties, research on knob shape coding has shown that certain shapes are easily discriminated and that these shapes can become associated with a particular knob function. Eckstrand and Morgan (1956) demonstrated that the association between a knob shape and a knob function can be facilitated by giving a nonsense syllable name to each knob shape. These results would lead one to expect that a meaningful association between shape and function would bring a more rapid association. However, in the past, knob shape and knob function often have been arbitrarily associated despite the success of the meaningfully coded flap and landing gear controls.

Meaningful shape and function associations could be direct, such as a tire-shaped knob used to control the raising and lowering of the wheels, or indirect, such as an *A* used to code an *a*irplane identification switch. To permit the use of more readily identifiable shapes, a remote association between knob shape and function could be facilitated by an intermediate association. For example, if an *A* cannot be easily identified tactually, the *a*irplane identification switch could be coded with a solid form similar to the shape of an *A*, a triangle. The triangle becomes associated with the *A*, which, in turn, is associated with the *a*irplane switch.

Purpose of Study

The present study evaluated the speed and accuracy of identification and operation of sets of knobs that were either meaningfully shape coded, arbitrarily shape coded, or noncoded. It was hypothesized that shape coding facilitates knob identification and, further, that a meaningful association is made sooner than an arbitrary association.

To avoid some of the shortcomings of earlier knob coding experiments, subjects were required to make absolute identifications; both speed and accuracy of identification were measured, and the time necessary to manipulate the various knobs was recorded. To approach the task load in the operation of an aircraft, each subject was required to monitor and respond to discrete visual commands concurrently. The nature of this loading task served to keep the subject's eyes occupied and provided an inferential measure of the amount of attention required for operating side-console switches with the various types of coding. It was predicted that meaningfully shape-coded knobs would interfere least with performance on the concurrent task.

METHOD

Three sets of four knobs designed for use in aircraft were evaluated. One set consisted of standard noncoded slab-sided rotary switch knobs. A second set of slab-sided knobs was arbitrarily coded on the sides with shapes that had been easily discriminated tactually in a preliminary study. An example of this method of coding is a grooved *X* used to identify the *station* knob. The third set of slab-sided knobs was meaningfully coded on top with letters that represented their functions. The letters were filled in to make them more discriminable. For example, the *A* used to code the *airplane* knob, when filled in as a solid figure, became a triangle. Based on the results of a preliminary study, ½-inch code shapes, ¼-inch high, were attached to the tops of the knobs. Exhibit 1 illustrates each shape-coded knob used.

Apparatus

Each set of knobs was installed on the right-side console of a cockpit simulator as shown in Exhibit 2. An experimental side-mounted flight stick with manual flight mode trigger also was located to the right of the subject. Photocells were positioned above the knobs. An electric timer, activated whenever the subject released the flight trigger, was stopped when the subject's hand broke the light beam above the correct knob.

Apparatus for the loading task was located on the left side of the instrument panel. Twelve red lights were spaced uniformly around a 12-position switch. A programmer provided eight random illumination sequences. The subjects were instructed to turn out lights by rotating the 12-position switch the shorter distance. A counter

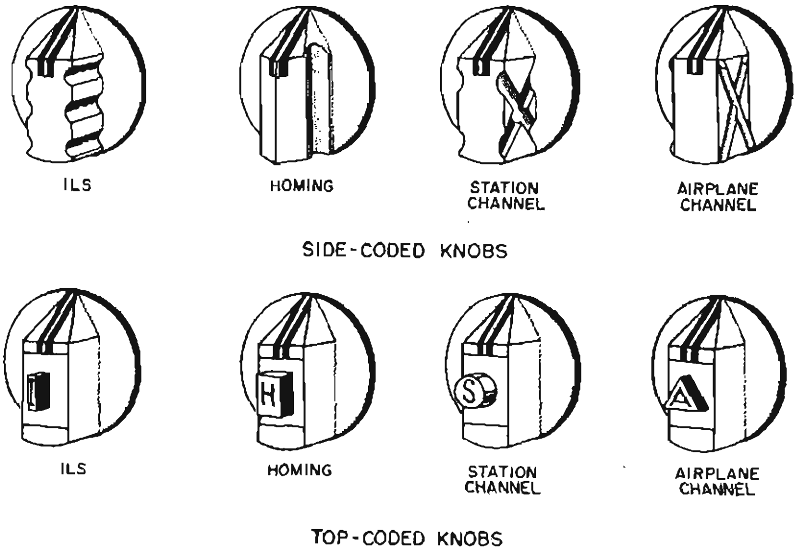

Exhibit 1. Shape-coded knobs used.

on the experimenter's panel recorded the number of times a subject turned out a light during either discrimination time or manipulation time.

Subjects

Twelve right-handed males were used in the investigation. The group represented three levels of experience with the experimental tasks and the cockpit simulator used. Three professional test pilots were familiar with the tasks involved and with the cockpit. Another group of three nonpilot engineers was quite familiar with the cockpit layout but was unfamiliar with the tasks required. A third group of six nonpilot engineers or draftsmen was entirely unfamiliar with both the apparatus and the tasks used.

Procedures

Each subject, wearing standard Air Force flight gloves, was seated in the cockpit simulator. He was told to keep his eyes on the left side of the instrument panel where the 12-light display was located. Whenever a light flashed on, he was to turn it out by rotating the 12-position switch the shorter distance.

While performing this task with his left hand, the subject was

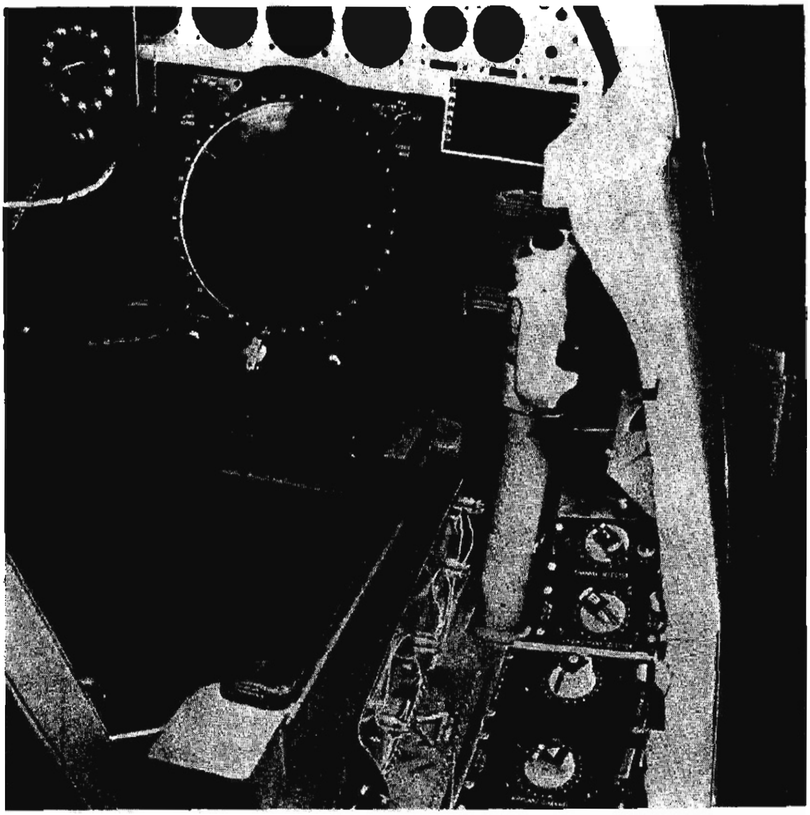

Exhibit 2. Switches with top-coded knobs attached, photo cells, prefocused lights, and side-mounted flight stick installed in the cockpit simulator.

given commands at irregular intervals to take his right hand from the flight trigger and identify and rotate a knob from the set of four on his right. Each command included which knob to locate and how far and in which direction to rotate it. After the knob was identified and rotated, the subject was to return his hand to the flight stick and depress the trigger.

Instructions on how to identify the correct knob varied according to the type of coding being used. All three knob types were ordered from the cockpit temperature control at the forward end of the console as follows: *ILS* knob, *homing* knob, *station* knob, and *airplane* knob. With the noncoded knobs, ordinal position was emphasized. To locate a noncoded knob, the subject had to count from the temperature control.

With the arbitrarily shape-coded knobs, the emphasis was on shape. The subject was to reach directly to a knob and confirm its identity by feeling the shape of its sides. The ILS knob had vertical grooves, the homing knob had horizontal grooves, the station knob had a grooved *X*, and the airplane knob had a raised *X*.

The meaningfully shape-coded knobs were also identified by shape, but emphasis was placed on the meaningful association between the knob function and the shape on the top of the knob. The subject was to reach directly to a knob and confirm its identity by the shape on top. The ILS knob had an *I*, represented by a thin rectangle; the homing knob had an *H*, represented by a thicker rectangle; the station knob had an *S*, represented by an oval; and the airplane knob had an *A*, represented by a triangle.

Experimental Design

The experiment consisted of four blocks of 48 trials each on the console switching task. Two blocks were given on each of two consecutive days. Sequence of presentation of the three knob types to different subjects was counterbalanced by the use of a Latin square design. On the first day, the initial knob type was presented for two blocks of 48 trials each, separated by a 5-minute rest period. This first knob type was repeated for two trial blocks to measure practice effects. On the second day, the remaining two knob types were presented for 48 trials each separated by a 15-minute rest.

Performance Measures

Three performance measures were used in the analyses. Substitution errors were counted whenever an incorrect knob was rotated. The time necessary to complete the console switching task was also measured. Total time was the period from the release of the flight trigger until the correct knob was rotated. The total time measure was divided further into discrimination time and manipulation time. Discrimination time was measured from the release of the flight trigger until the correct knob was touched. The time from contact with the correct knob until it was rotated was termed manipulation time.

Assessment of performance on the loading task was made by calculating the number of times per minute of discrimination or manipulation time that a red light was turned out. Because the loading task was performed only while the subject was identifying or manipulating a knob, loading-task total scores were measured over varied time intervals. The standard time measure guarded against inflating the loading-task performance of subjects requiring longer to complete the console switching task.

RESULTS

An essential characteristic of a method of coding is that few errors result from its use. In an aircraft, the manipulation of an incorrect knob can be fatal.

Substitution Errors

Substitution errors in the first two blocks of 48 trials were analyzed by the type of knob coding used. A Kolmogorov-Smirnov test indicated that significantly fewer errors were made while using the meaningfully top-coded knobs than while using either the arbitrarily side-coded knobs or the noncoded knobs during the initial block of trials ($p < .05$). During the second trial block, the numbers of substitution errors did not differ significantly among the three types of knobs. Exhibit 3 summarizes these results.

Exhibit 3. Number of substitution errors for each type of knob coding (Trial Blocks 1 and 2).

Trial Block	Knob Type		
	Non-coded	Side-coded	Top-coded
1	15	23	0
2	3	1	1

The effects of practice on the number of substitution errors committed were evaluated by examining the number of such errors in each trial block. A Cochran Q test showed practice effects to be significant ($p < .05$). Substitution errors decreased as the subjects repeated the task. The largest decrease occurred from the first to the second trial block.

Time

A minimum of time to identify and manipulate knobs in aircraft is essential. If a knob coding system interferes with rapid identification and manipulation, the system is detrimental. Thus, the time necessary to complete the console switching task is a necessary performance measure.

Time scores by type of knob coding were analyzed in Trial Blocks 1 and 2 by means of a Kruskal-Wallis test. Neither total times nor manipulation times differed significantly among the knob types in either trial block. However, the interaction of discrimination time by type of coding was significant in both trial blocks ($p < .05$). Exhibit 4 depicts the initial time requirements of each type of coding.

Exhibit 4. Means of median time scores for each type of knob coding (Trial Blocks 1 and 2).

Time Measure (sec.)	Trial Block 1			Trial Block 2		
	Non-coded	Side-coded	Top-coded	Non-coded	Side-coded	Top-coded
Discrimination	1.84	1.06	0.99	1.84	0.74	0.81
Manipulation	1.22	1.56	1.96	1.14	1.08	1.83
Total	3.22	2.85	3.24	3.10	1.91	2.78

A second analysis of time by type of coding was based on the time scores in the last three trial blocks. Exhibit 5 summarizes these scores. A Friedman two-way analysis of variance demonstrated that both sets of coded knobs required significantly less discrimination and total time than did the noncoded knobs ($p < .05$). However, the meaningfully top-coded knobs required more manipulation time than the other two types of knobs ($p < .05$).

Exhibit 5. Means of median time scores for each type of knob coding (Trial Blocks 2, 3, and 4).

Time Measure (sec.)	Knob Type		
	Non-coded	Side-coded	Top-coded
Discrimination	1.94	0.84	0.80
Manipulation	1.09	1.36	1.56
Total	3.12	2.32	2.55

The overall effect of practice on time scores, regardless of experimental condition, was analyzed by a Friedman two-way analysis of variance by ranks. There was no significant change in total time or discrimination time over the four trial blocks. However, with practice less time was necessary to set the knobs ($p < .05$).

Loading Task

An important, but often neglected, criterion of knob coding efficiency is the interference of coding with performance on other concurrent tasks. Despite having been given similar instructions, the subjects differed widely in their performances on the loading task. Five subjects who essentially ignored the task were eliminated from analyses of loading-task performances.

Loading-task scores in the final three trial blocks were analyzed by a Friedman two-way analysis of variance. Concurrent loading-task performances differed significantly while using the three different types of console switch knobs ($p < .05$). A comparison of pairs of coding conditions indicated that meaningful top coding produced less loading-task interference than did noncoding. These results are summarized in Exhibit 6.

Exhibit 6. Loading task scores for each type of knob coding (Trial Blocks 2, 3, and 4).

Item	Knob Type		
	Non-coded	Side-coded	Top-coded
Total Score	156	158	194
Total Time (min.)	16.05	11.25	11.62
Average Score per Minute	9.7	14.0	16.7

Unlike knob identification, performance on the loading task did not improve with practice. A Friedman rank analysis by trial blocks of the scores of the seven subjects who performed the loading task showed no significant changes in performance over time.

DISCUSSION

An evaluation of any method of knob coding should consider several factors.

Original Learning

Of great importance is the amount of training required to learn the system. Ideally, a coding system should require little or no training. The substitution error scores in this study imply that the meaningful coding system was used immediately with few errors. The noncoded and arbitrarily coded knobs, however, required practice to memorize either the knob location or knob shape.

Realistically, the number of times a particular knob in an aircraft is used for any one flight might be very low. Therefore, although these results show that substitution errors with all knobs were essentially eliminated by the end of 48 trials, the switches, in actual operation, might be used only occasionally. Many flights might occur before the identification system is learned during which critical errors could be made.

Strength of Response

In addition, a response that requires a great deal of training is not durable under stress or resistant to forgetting with disuse. Research on code compatibility suggests that a coding system compatible with population response stereotypes is easily learned, because less encoding of information is required (Fitts and Seeger, 1953). Under stress such stereotyped responses are more apt to persevere than responses which require more learning (Lazarus, Deese, and Osler, 1952). The results of this study suggest that meaningful shape coding is more stereotypic than either arbitrary shape coding or noncoding. Because the operation of an aircraft requires the processing of a great amount of information, the knob coding system that provides the most direct encoding of information is to be preferred.

Residual Attention

Another major factor in selecting a knob coding system is the amount of attention it requires. Aircraft operation is a complex task made up of many subtasks of various priorities. In general, no single operation can be permitted to occupy a pilot's attention entirely. The amount of attention left over from one task that can be used to attend to other tasks has been termed residual attention (Damos and Roscoe, 1970). The loading task served as a measure of residual attention in this study. The fact that performance on the loading task was best when the subjects were using the meaningfully shape-coded knobs indicates by inference that pilots would be able to perform other cockpit tasks better while using meaningful shape codes.

Speed of Operation

Regardless of the accuracy of identification with a knob coding technique, it must also be efficient in speed of operation. Traditionally, the use of unusually shaped knobs has either increased the time required to manipulate a knob or interfered with the accuracy of the setting (Hunt and Warrick, 1957). To some extent this problem occurred with the meaningfully coded knobs; significantly more manipulation time was required for operating them. However, the discrimination time needed with the meaningful knob shapes was so much less than with the other types of knobs that the total time requirement was significantly less than with the noncoded knobs. Bradley (1967) has investigated how much the texture, diameter, and thickness of a knob can be changed without interfering with the speed and accuracy of manipulation. It is quite possible that the shape limitations found by Bradley could be used in designing meaningfully shape-coded knobs that do not inflate manipulation time.

Overall, the meaningful shape coding system required the same total time for discrimination and manipulation as arbitrary shape coding and less total time than noncoding. Further, the meaningfully coded knobs were identified more quickly and surely, and their use resulted in significantly more residual attention to devote to other tasks.

IMPLICATIONS

In the past, aircraft designers have been reluctant to use shape-coded knobs because of the obvious logistics and maintenance problems. If knobs and shafts are interchangeable, one shape-coded knob could be replaced by another, greatly increasing the risk of substitution errors by the pilot. On the other hand, the cost of building and maintaining an aircraft is increased when shafts and knobs are keyed; stocking many different kinds of knobs is troublesome as well as costly. However, such cost and bother might be justified by the demonstrated advantages of meaningfully coded knobs.

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Time-Compressed Displays for Target Detection

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INTRODUCTION

Historically, the effectiveness of radar has been limited because of the difficulty operators have in discriminating target echoes from noise and clutter. Weak echoes returned by distant aircraft are difficult to distinguish from radar noise, and low flying targets are difficult to discriminate from the clutter of echoes from fixed reflectors on the ground. These problems have been solved partially by the use of sophisticated and expensive electronic signal processing; however, much improvement still needs to be made. If target returns could be made more conspicuous, the effective range of radar could be increased substantially. In addition, operator workload would be reduced and, with it, the probability of catastrophic errors. Such improvements may be realized by matching the display to the perceptual system of the operator.

Background

On a radar display, targets, noise, and clutter frequently are not distinguishable from one another on the basis of size, shape, or intensity, which means that targets must be identified solely by their coherent motion. Such identification is difficult because practical scan rates are too slow to allow the operator to look directly for coherent motion. Instead he must select a return, watch it for several scans of the antenna, and verify that it is moving. Obviously, if the noise or clutter level is very high, a large number of false returns will be followed before an actual target is found.

The task of detecting a target on a ground-based radar display consists primarily of discriminating coherent target motion from both the noncoherent, randomly appearing noise and the clutter of stationary returns from the surrounding terrain. On an airborne radar display, the clutter also has coherent motion but of a rate different from that of airborne targets. A display that accentuates the coherent motion of targets relative to the random noise and slowly moving clutter ought to yield improved detection performance.

Antenna scanning. A typical air-to-air search radar scans a limited sector in front of the aircraft. Generally, the sector covers a horizontal angle of not more than 130 degrees centered about the aircraft's flight path as indicated in Exhibit 1. To provide the required

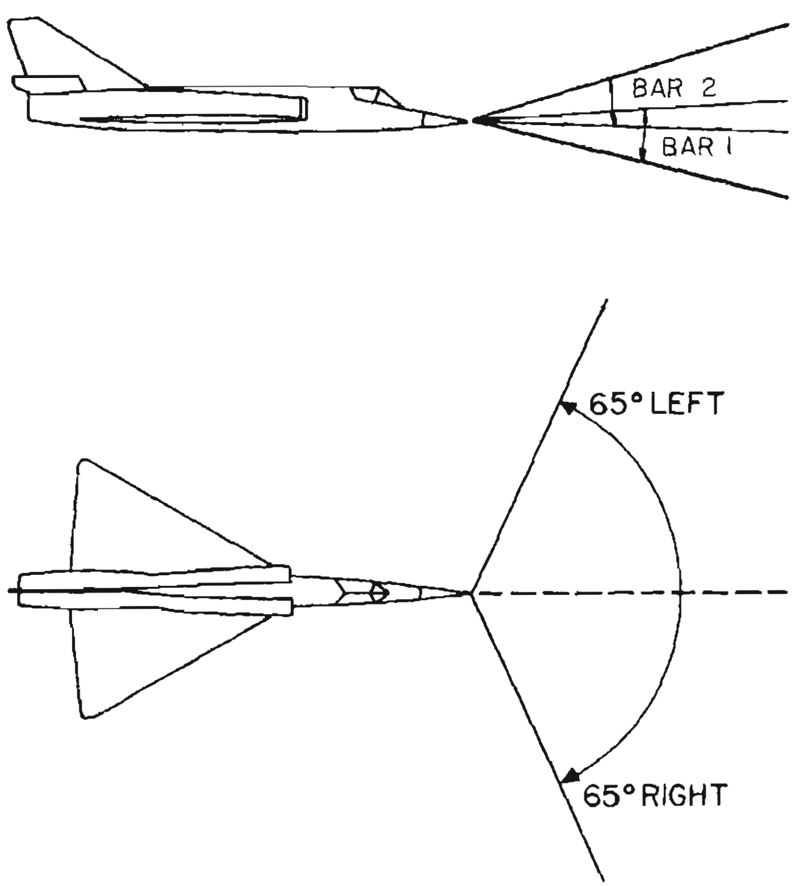


Exhibit 1. Typical air-to-air radar antenna azimuth scan limits and elevation scan-bar arrangement.

search coverage in elevation, the *azimuth sector* just described may be scanned at various elevation angles, known in radar terminology as *elevation bars.*

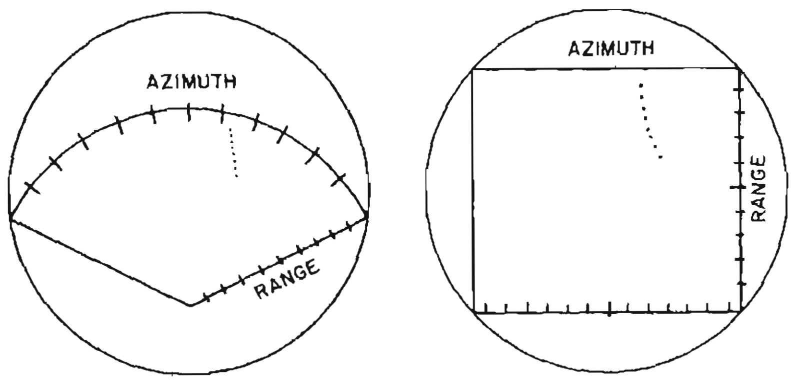
Separation between successive elevation bars is usually limited to somewhat less than the vertical angle subtended by the antenna's transmitted beam to ensure vertical overlap of adjacent scan sectors and to avoid gaps in the search pattern. Successive elevation bars are usually scanned in opposite directions. A complete azimuth and elevation scan cycle of an air-to-air radar is known as a *frame.*

Because the antenna follows this complex repetitive cycle, a target may appear on one azimuth scan or two successive scans and then not reappear until the antenna has scanned all other elevation bars and returned to the bar on which the target originally appeared. If the antenna were programmed to scan eight elevation bars, a large but not unreasonable number, a target might appear once or twice and not reappear for several seconds.

The display of radar echoes. The range of a target is directly proportional to the delay between the transmission of a radar pulse and the return of its echo. Thus, it is possible to present a plan view of the sector scanned by an antenna on a cathode ray tube display as shown in Exhibit 2a. Such a presentation, called a *sector PPI* (plan position indicator), presents radar returns in polar coordinates with the origin at the aircraft.

A more common air-to-air search presentation, called a *B-scan* display, transforms the polar-coordinate sector PPI into Mercator coordinates in which all rays emanating from the origin are parallel. Range in miles and azimuth in degrees are presented orthogonally, as shown in Exhibit 2b.

How operators search for targets. If radar observers are asked to develop a strategy for finding targets on a B-scan air-to-air radar display, most will report that they watch the range-sweep line as it scans from left to right or right to left in the process of updating the display. With a scan-converted display, if the returns from one scan are stored and displayed without decay until replaced by the incoming returns from the next scan (selective erasure), the target will appear to jump a small fraction of an inch as the range sweep crosses it the second time. The jump results from the target's movement in space during the interval between successive illuminations by the antenna. Skilled operators track the moving interface between the old and new scans and watch for the jump.



(a) Sector PPI display. (b) B-scan display.

Exhibit 2. Comparison of sector PPI and B-scan radar displays showing pattern of target returns from eight successive antenna scans.

Preliminary Work

Evidence that the rapid jump of the target aids detection was obtained from informal studies performed in preparation for the experiment to be reported. Each subject was asked to detect targets using a scan-converted display on which the target made either one jump or two. The single-jump condition was equivalent to the normal updating of a display in the manner just described. The double-jump condition occurred as a simulation accident resulting from the particular method used to generate targets.

Normally, the interval between presentations of the same target on successive scans depends upon its azimuthal distance from either side of the display: the closer to the edge (where the antenna reverses its scan direction), the shorter the interval, resulting in a shorter target jump. In the simulation, however, all target position updating was done almost simultaneously with the antenna turnaround, producing equally spaced returns for all targets having a given relative velocity regardless of azimuthal position. This simulation technique generates a double jump on a scan-converted presentation for targets close to either the right or left edge of the display. An examination of performance data on single-jump versus double-jump presentations indicated that the probability of target detection is greatly increased by the second jump.

The jump obtained is an example of the type of visually apparent motion referred to as the *Phi* phenomenon. Although the sensory mechanism is not well understood, Spigel (1965) reported spot intensity, spacing, and rate of alternation as important variables affecting the perception of apparent motion. Similar observations were made by Wertheimer (1912) who coined the term *Phi.*

Enhancement of Target Detection

There is ample empirical evidence that the phenomenon of apparent motion would provide an effective means of enhancing the detection of radar targets if their slow scan-to-scan or frame-to-frame motion could be displayed in fast time. In 1956, C. T. White, at the Naval Electronics Laboratory, dramatically demonstrated the power of visual time compression to give targets apparent motion resulting in their increased detectability. He filmed successive scans of a radar display for playback at faster rates in a standard movie projector. The results were spectacular: aircraft flying well beyond the accepted range of the particular radar were readily recognized. In addition, much of what appeared to be noise at standard presentation rates revealed readily identified informational content when time compressed. As an example, sea gulls flying around fishing boats appeared as noise with a standard display but could easily be recognized and identified with the time-compressed display. Time compression accentuated relevant information and attenuated noise and clutter (Naval Electronics Laboratory, 1956; White, 1956).

Photographic visual-time-compression techniques have limited usefulness for real-time display despite the existence of extremely rapid film development systems. However, motion cues can be utilized in a practical real-time presentation if several past frames are stored and played back in the same order as they were collected but at a faster rate. If these frames are repeatedly played back at an appropriately fast rate, returns from a moving target appear as a rapidly moving dot traversing the display. The dot, first evident in the oldest frame, moves across the display until it appears in the most recent frame. The dot motion then starts over, appearing on the oldest frame again, and retraces its path.

While this sequence is being played back in fast time, the display is updated with new information gathered in real time. Each new frame replaces the oldest frame so that only the desired number of preceding frames is stored for display. The overall effect is that of a repetitive moving dot sequence that slowly advances across the display. The rapid motion of the dot adds to the conspicuousness of the target, while the slower motion of the coherent dot sequence keeps the target position current. This type of real-time visual-time compression has been demonstrated by the MITRE Corporation using a computer-generated cathode ray tube display (Smith, 1966). However, no experimental study of operator performance as a function of time-compressed display variables was performed.

Experimental Studies

At NELC. Recently, Chandler and Harris (1970) of the Naval Electronics Laboratory Center have developed a Time-Compressed Display System (TICODS) that utilizes a video disc recorder to store radar or other successively recorded images. The system accepts an input from a radar scope by means of a television camera, performs the time-compression transformation, and outputs to a standard television monitor or to a video tape recorder. A second output provides a standard radar display.

Up to 36 frames of video can be stored by the unit. Thirty-two of these are controlled sequentially by the logic section; the remaining four can be controlled manually. One of these four may be used to store the last frame, thereby allowing the current frame of information to be displayed continuously. The unit also allows selection of the number of past frames to be stored and the rate at which they are to be played back (time-compression ratio).

The TICODS equipment has been used by the Naval Electronics Laboratory Center in an evaluation of time-compressed displays. Stimulus materials were video tapes made from the TICODS system. Both a short-range surface-search radar and a medium-range air-search radar were used. The experimenter analyzed these tapes to find and plot all of the airborne targets. Both novice and experienced subjects were then required to detect and track targets presented either on a regular display or on a time-compressed display. The tracks were recorded on a clear acetate overlay with a grease pencil. Each subject's overlay was compared with the master made by the experimenter, and the percentages of targets detected and tracked were calculated. Experimental data concerning the optimum number of prior image frames and time-compression ratio are classified due to the particular radar and personnel used. However, data available in the open literature indicate that operator performance in detecting and tracking targets doubles when time-compressed displays are used (Milroy, 1970).

At Hughes Aircraft. Opittek (1970) studied a special case of time compression using four frames of stored air-to-air radar imagery. Instead of playing back these frames in their proper temporal sequence, all frames were summed and presented simultaneously. If the time-compression ratio is defined as the time required to collect a given number of image frames divided by the time during which they are played back, the time-compression ratio approaches infinity as the presentation of all frames becomes virtually simultaneous. With this type of display, targets are recognized by their linear pattern of dots.

Opittek measured the probability of detecting a target for zero-frame, one-frame, and four-frame storage with various false alarm rates, or noise levels, and two target velocities. One-frame storage corresponds to a scan-converted display and zero-frame storage to a standard real-time display without scan conversion. Opittek found a significant increase in the probability of detection as the number of stored frames increased. Performance differences became more pronounced as the noise level increased from its low of one blip per frame to its high of five blips per frame. Target velocity was less important on a display with four frames of storage than on one with only a single frame of storage. Opittek concluded that, at the higher noise levels, storing past radar histories significantly improves detection performance; however, at the lower noise levels, the task is not sufficiently difficult to warrant storage.

Experimental Questions

Previous research clearly demonstrates that there is a gain in detection performance when visual time compression is used. However, a need exists for information concerning the effects of numerous time-compression variables upon detection performance and how these variables interact with one another. In addition, time-compression phenomena must be related to our existing knowledge of the human perceptual process. The experiment described here is a first step toward finding solutions to these problems. This experiment investigated the effects of time-compression ratio, number of stored frames, clutter level, noise level, target direction, target speed, and various interactions among these variables.

METHOD

Visual time-compression phenomena were investigated using a simulated radar display with electronically generated targets, noise, and clutter in a target detection task. A simple, single-bar antenna search frame was simulated to facilitate manipulation of variables of immediate experimental interest. The simulator generated a rectangular range versus azimuth angle, or B-scan, display with thresholded video. The thresholded video technique, commonly used as a means of reducing visible noise, results in a display with a single level of spot intensity. Any signal coming out of the radar receiver that is above a prescribed threshold is displayed with full intensity, while any signal that is below threshold is not displayed at all.

The electronically generated targets were further simplified in that they followed a straight path across the display, and there was constant spacing between successive returns. The difference between a straight path and the slightly curving target path typical of a B-scan presentation is minor if the range of the target is large, as was the general case in this study. The constant spacing between returns is a concern only when targets are close to the edge of the display as discussed in the introduction. Such simplifying abstractions produce more consistent stimulus conditions, thereby allowing greater control and easier interpretation of the results in terms of the perceptual process.

Apparatus

A Hughes Aircraft Company digital scan converter, modified to allow for the storage of 1, 4, 8, or 16 frames of radar imagery and to provide time-compression ratios from unity to infinity, was used. Three sources of input to the converter were provided: one for targets, one for noise, and one for clutter. Output was fed to a cathode ray tube viewed by the subject.

Targets were generated electronically. Starting positions, range rates, and azimuth rates of targets could be selected by setting a series of switches. All targets closed in range but could either progress from left to right or from right to left in azimuth. All target updating was done while the antenna was reversing its direction on either the left or the right side of the display. This technique gave equal spacing between target returns.

Random noise was generated using a Gaussian noise generator calibrated so that a particular number of pulses per second (blips) could be obtained by setting a 10-turn potentiometer.

The clutter input to the digital scan converter came from a flying spot scanner that normally converts images on film to video signals. In this case, the imagery consisted of a continuous paper belt with pin holes punched into it allowing light to pass through. Each hole simulated one clutter return. Because an airborne radar was simulated, the paper strip was slowly moved through the flying spot scanner to simulate motion of the clutter relative to the aircraft. The electric motor driving the paper ran through a reduction gear train which allowed the speed to be changed, thereby varying the apparent speed of the aircraft over the ground. The pin hole positions were selected using a random number table to obtain x and y values of the hole positions. The only constraint placed on the selection was that the density of holes be uniform for all frame-size areas throughout the strip.

All three classes of inputs—targets, noise, and ground clutter—yielded identical dots on the display with respect to size, shape, and intensity. The three could be differentiated only on the basis of the changes in their positions on the display as time progressed.

Targets, noise, and clutter were presented on a $4\frac{1}{2} \times 4\frac{1}{2}$-inch raster generated on a cathode ray tube (CRT). The CRT had a P-31 phosphor which has a very fast decay (one millisecond to 30 percent of peak intensity) and a green color. Typical spot brightness was 35 millilamberts; background brightness was 2.2 millilamberts. Ambient room lighting was subdued and constant for all conditions. Provisions were made for the unblanking of the display by the experimenter at the beginning of a trial and for the blanking of the display either when the subject pressed a hand-held button or when the experimenter actuated a switch to terminate a trial.

In front of the display was a plastic face plate on which was etched a 14×14-line grid. Letters were etched along the sides to identify rows, and numbers were etched across the top and bottom to identify columns. When the display was blanked, red edge-mounted lights were turned on to illuminate the grid. When the display was unblanked, the lights were turned off, and the grid was barely noticeable. When illuminated, this grid was used by subjects to identify the position of a target by specifying the letter-number combination corresponding to the particular square containing the most recent target return. The grid technique of target designation was used to minimize any confounding of the detection task with an acquisition task.

A second display, beyond the subject's view, presented only targets. This allowed the experimenter to determine the correctness of a subject's response. In addition to the switches to blank and unblank the subject's display, the experimenter had access to a silent switch that initiated the appearance of the target. The first target return to appear, after the silent switch was depressed, automatically started a silent clock that measured detection latency. The clock consisted of a counter and a 100-Hz square wave oscillator. The clock stopped automatically when the subject pressed his hand button. The accuracy of the clock was checked periodically against a stopwatch.

Experimental Design

A mixed-model design was used in which six factors, time-compression ratio, frame storage, clutter level, noise level, target direction, and target speed, were completely crossed; a seventh factor, subjects, was nested within the frame-storage factor. A completely crossed design would have been required to assess all interactions among the variables. However, for each subject to be tested under all treatment combinations would have required over 12 experimental hours per subject. To reduce the time required of each, subjects were nested within the frame-storage variable, resulting in three groups of six subjects, one for each of the frame-storage conditions.

Six time-compression ratios between unity and infinity were used. With a time-compression ratio of one, only the immediately preceding frame is stored, and the display shows the stored frame for the interval of time required to record the next frame. This conventional scan-converted presentation was included as a control condition against which the time-compressed displays could be compared. A time-compression ratio of infinity is the terminal case in which all stored frames are presented simultaneously as in Opittek's four-frame-storage condition. Between unity and infinity, four other time-compression ratios were chosen to yield varying degrees of apparent motion. These ratios were 4:1, 12:1, 24:1, and 48:1.

Three levels of random noise, 16, 32, and 48 blips per frame, and two levels of clutter, 5 and 10 blips per frame, were used. These levels were selected on the basis of pretest results to yield a primary task sufficiently difficult to eliminate the need for a side task. As a result, the noise levels are somewhat higher than one might expect from a good radar.

Within each cell, six trials were required. The last four trials contained the factorial combinations of two target directions and two target speeds. Because targets closed in range, the direction variable refers to whether a target had azimuth motion (angled) or not (straight). The two target speeds appeared as dot trails of different lengths. The first two trials contained both directions but only one of the two speeds. Angled targets, starting on the left half of the display, angled from left to right; those starting on the right, angled from right to left.

A sequence of 216 different targets was made up so that each subject saw a particular target only once. This sequence was subjected to three constraints: (1) half of the targets started on the right half of the display, and half on the left; (2) equal numbers of targets had each of the four combinations of direction and speed; (3) all targets had to be present for at least 40 seconds (this excluded the initial appearance of targets at close range).

The time-compression-ratio variable was counterbalanced using a 6 × 6 Latin square. The six subjects within each level of frame storage comprised one factor, and the six time-compression ratios, the other factor. This generated a situation in which every display followed every other display once and only once across the six subjects. A second Latin square counterbalanced the six noise level sequences. The six combinations of three noise levels taken three at a time (ABC, ACB, BAC, BCA, CAB, CBA) made up one factor of the 6 × 6 Latin square, and subjects provided the second factor. Consequently, each of the six possible orders of noise levels followed every other order once and only once. Noise counterbalancing was superposed on time-compression-ratio counterbalancing. Because of the mechanical difficulty in changing clutter level, clutter density was altered between the first and second halves of the 216 trials each subject received. Alternate subjects saw the clutter density of 10 first. The numbers of stored frames were counterbalanced by randomly assigning the six possible orders of the three conditions to three subjects at a time. For example, the first three subjects received 4, 8, and 16 frames of storage in that order, while the second three subjects received 4, 16, and 8 frames of storage in that order.

Subjects

Fourteen technical personnel from Hughes Aircraft Company and four technical personnel from other aerospace companies in the Los Angeles area served as subjects. Subjects were randomly assigned to one of three groups. All subjects were naive with respect to radar target detection using time-compressed displays. Each subject was tested in four blocks of trials requiring approximately one hour each. A 10-minute rest period was provided after the first and third hours. A one-hour lunch break separated the second and third trial blocks.

Procedure

Prior to his experimental trials, a subject was read a standard set of instructions and shown the various display conditions. He was then given sufficient practice to insure that he understood the task and was familiar with the target characteristics. On these practice trials a subject was asked to find the target just as in a regular trial; however, if he failed to do so, the trial was started over and the target pointed out to the subject. Additional practice trials were given each time the time-compression ratio was changed but not between changes in noise level.

Each subject was given six experimental trials in each of the 36 treatment combinations. The experimenter announced the beginning of a trial, then unblanked the display which presented noise and clutter but no target. The target was introduced with a variable delay not exceeding 20 seconds in accordance with a list of random numbers. The subject was allowed to view the display for 40 seconds following the first target return. If the subject detected what he believed to be a target, he pressed a hand-held button that blanked the display, illuminated the grid, and stopped the clock. The subject then reported the position of the target by specifying the letter-number combination corresponding to the square containing the target.

Once the subject had identified a particular square, the experimenter verified the correctness of the response using the display that presented the target only. The experimenter recorded the time to detect the target and whether the response was correct or incorrect. In the event that the subject failed to detect a target within 40 seconds, the experimenter blanked the display and recorded a miss. During the 40 seconds or less that the subject searched for the target, the experimenter set up the starting position, direction, and speed of the target for the next trial.

RESULTS

Radar target detection performances differed reliably ($p < .01$) as a function of each primary experimental variable; these included number of stored frames, time-compression ratio, noise level, and clutter level. Performances associated with two secondary experimental variables, target direction and target speed, were analyzed separately, but neither showed a significant main effect ($p > .05$).

Effects of Primary Experimental Factors

Performance measures included detection latency, false detections, and misses. For the initial analysis of detection latencies, the time-to-detect scores for the six trials in which there were variations in target direction and speed were averaged for each subject in each condition. Variances of the resulting scores, tabulated in Exhibit 3, were analyzed with time-compression ratio, number of stored frames, clutter level, noise level, and subjects as factors. A summary of this analysis is presented in Exhibit 4.

Misses and false detections during the six trials by each subject in each condition were also counted and analyzed. Results from the various performance measures follow.

Time to detect. In the analysis of detection latencies, missed targets and false detections were both assigned values of 40 seconds. In the case of misses, this is a reasonable score because it is the maximum time a subject was allowed to search for a target. There is, of course, no way of knowing how much longer he might have searched without success had he been given the opportunity. When a subject detects something other than a target, the appropriate latency score is less apparent. The time at which the subject makes the false detection is not an adequate measure because, in some cases, the false detection may be made before the target is introduced. Further, it seems necessary to add some penalty for false detections because, in an operational situation, the tracking of a false target requires time that could otherwise be used searching

Exhibit 3. Summary tabulation of detection data. Means for six trials.

Time-Compression Ratio	Clutter Level (Returns per Frame) 5			Clutter Level (Returns per Frame) 10		
	Noise Level (Blips per Frame)			Noise Level (Blips per Frame)		
	16	32	48	16	32	48
	4 Stored Frames					
1: 1	31.3	32.5	35.5	28.9	32.8	34.5
4: 1	31.3	35.8	36.5	31.1	36.2	35.7
12: 1	25.1	30.1	34.4	23.4	28.9	32.9
24: 1	21.1	24.8	33.9	18.3	29.2	32.4
48: 1	16.9	24.2	27.6	15.8	22.7	27.3
inf.	15.1	20.5	25.1	15.6	21.5	24.0
	8 Stored Frames					
1: 1	23.7	32.6	35.9	28.8	34.1	35.0
4: 1	18.9	24.7	27.3	23.4	26.1	27.4
12: 1	13.2	16.4	16.7	16.9	17.4	21.1
24: 1	12.9	15.8	16.4	13.9	15.1	17.9
48: 1	13.4	15.0	15.9	12.0	15.0	16.8
inf.	12.9	12.8	16.5	12.6	12.8	17.0
	16 Stored Frames					
1: 1	27.7	31.4	36.1	30.3	33.4	35.3
4: 1	25.0	27.2	28.4	31.2	29.9	35.8
12: 1	16.2	18.4	19.1	19.2	20.6	21.9
24: 1	14.5	14.4	16.0	15.7	15.0	19.9
48: 1	13.5	16.4	17.3	17.3	17.6	19.1
inf.	11.5	15.2	15.2	13.5	16.8	17.6

for a real target. With these considerations in mind, the latency for false detections was arbitrarily set at 40 seconds.

Three factors, number of frames stored, time-compression ratio, and noise level, were found to have pronounced effects on the time required to detect a target, as shown by the summary data tabulated in Exhibit 3. The fourth factor, clutter, caused only a slight change in time to detect. Three two-way interactions among the variables and one three-way interaction were also found to influence the time required to detect a target. The analysis of variance summarized in Exhibit 4 indicates that all of these effects would be expected to occur by chance less than once in a hundred replications of the experiment ($p < .01$).

Exhibit 5 graphically presents the effects of time-compression

Exhibit 4. Analysis of variance summary for mean time to detect for six trials.

Source	df	MS	F
Between Subjects			
Frames Stored (FS)	2	3773.81	9.30*
Subjects (S/FS)	15	405.90	
Within Subjects			
Clutter (C)	1	187.39	13.14*
FS × C	2	139.97	9.82*
S/FS × C	15	14.26	
Time-Compression Ratio (TCR)	5	4554.98	126.26*
FS × TCR	10	206.84	5.73*
S/FS × TCR	75	36.08	
Noise (N)	2	1917.78	162.82*
FS × N	4	128.38	10.90*
S/FS × N	30	11.78	
C × TCR	5	14.57	0.88
FS × C × TCR	10	11.52	0.69
S/FS × C × TCR	75	16.58	
C × N	2	2.46	0.21
FS × C × N	4	18.18	1.51
S/FS × C × N	30	12.01	
TCR × N	10	7.25	0.62
FS × TCR × N	20	33.15	2.82*
S/FS × TCR × N	150	11.75	
C × TCR × N	10	7.74	0.79
FS × C × TCR × N	20	8.17	0.83
S/FS × C × TCR × N	150	9.81	

* $p < .01$

ratio as a function of the number of stored frames. Results relating to the number of stored frames indicate a sharp drop in time to detect when going from one to four stored frames, as found by Opittek (1970). There was a second, even larger, drop between 4-frame and 8-frame storage, but a slight loss was incurred in going to 16-frame storage. A Newman-Keuls analysis showed all points to be significantly different from one another ($p < .05$).

It is interesting to consider these results in terms of the number of target returns required before detection of the target occurred. With 8-frame storage, the mean time to detect was 17.1 seconds, which corresponds to 10.2 target returns; one return occurred every scan of the antenna, which took 1.67 seconds. With 16-frame

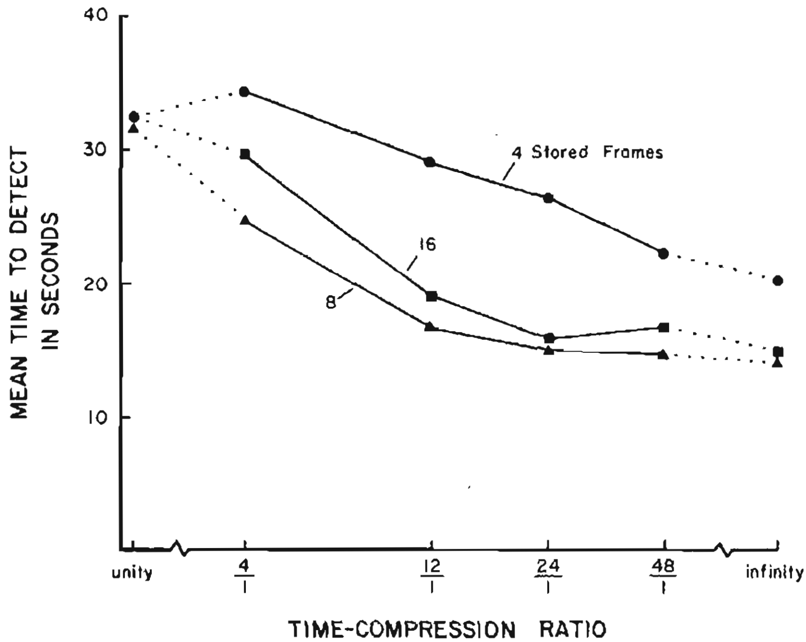


Exhibit 5. Effect of time-compression ratio and number of stored frames on time required to detect a target based on the means of six trials by each of 18 subjects.

storage, the mean time to detect was 19.3 seconds, which corresponds to 11.5 returns. On the average, a subject found a target when it was 11 or 12 dots long, and the additional four or five frames of storage collected prior to the initial appearance of the target contained only noise and clutter. This is probably the reason for the increase in time to detect with 16-frame storage. The noise level in terms of the number of dots on the display was twice as great as with 8-frame storage, but the subject made a detection before he could take full advantage of the increased target information. Results from this experiment indicate that the optimum number of frames to store is between 8 and 16, with 10 to 12 the most likely value based on the average number of returns required to find the target.

A review of the effects of time-compression ratio on the time required to detect a target indicates a monotonic decrease as the time-compression ratio increases from unity to infinity. A Newman-

Keuls analysis indicated that all points were reliably different from one another ($p < .01$). Data for 8-frame and 16-frame storage can be approximated by two straight lines intersecting between time-compression ratios of 12:1 and 24:1. The first line, fitted between time-compression ratios of 1:1, 4:1, and 12:1, has a steep negative slope indicative of rapid decreases in time to detect with small increases in time-compression ratio in this region. The second line, connecting time-compression ratios of 24:1, 48:1, and infinity, is nearly flat. The breakpoint where the two lines intersect corresponds to a presentation rate approximately halfway between 70 and 140 milliseconds per frame. These values are those obtained from time-compression ratios of 24:1 and 12:1 and are calculated by dividing the antenna update rate of 1.67 seconds per frame by the time-compression ratio.

A nearly linear relationship between noise level and time to detect a target was found. As expected, the higher the noise level, the more difficult the task. The minimal effect of clutter on time to detect a target was probably due to the small difference in the two levels of clutter simulated.

Exhibit 5 clearly shows the interaction between the number of stored frames and time-compression ratio. It is evident that the interaction is due to the unique effect of 4-frame storage. Curves for 8-frame and 16-frame storage show a breakpoint around a time-compression ratio of 12:1, as discussed earlier. Performance with 4-frame storage does not indicate any such change in slope. A Newman-Keuls analysis shows that the only reliable difference ($p < .05$) is between time-compression ratios of 4:1 and infinity for 4-frame storage. Apparently 4-frame storage has a different perceptual effect from 8-frame and 16-frame storage.

Three other interactions were found to be significant ($p < .01$), and in every case the interaction is a result of a difference between 4-frame storage and the other conditions, again indicating a difference in the perceptual task.

Misses. Because the number of misses is negatively related to frequency of detection, it provides a basis for estimating probability of detection. Furthermore, examination of an individual observer's misses and false detections reveals his detection strategy. If he is conservative, he will have long detection latencies but few misses and virtually no false detections; if he is reckless, he will have short detection times but many false detections and consequently many misses.

Analysis of the number of missed targets per six trials indicates that number of stored frames, time-compression ratio, and noise level had significant effects ($p < .01$), as did several interactions. Except for minor differences, these curves are comparable to those obtained using time to detect as the criterion. Although the difference between 8-frame and 16-frame storage was not significant, the minimum number of misses would still be expected to occur between 8 and 16 frames.

The differences caused by time-compression ratio are more dramatic when number of misses is the criterion than when time to detect is used. Exhibit 6 shows the interaction of time-compression ratio and number of stored frames; the differential effect of 4-frame storage is apparent.

False detections. Analysis of the number of false detections per six trials yields only one significant ($p < .01$) effect, time-compression ratio, as graphed in Exhibit 7. Here a reliable minimum is apparent at a time-compression ratio of 24:1 ($p < .05$). The occurrence of the minimum is more in line with what would have

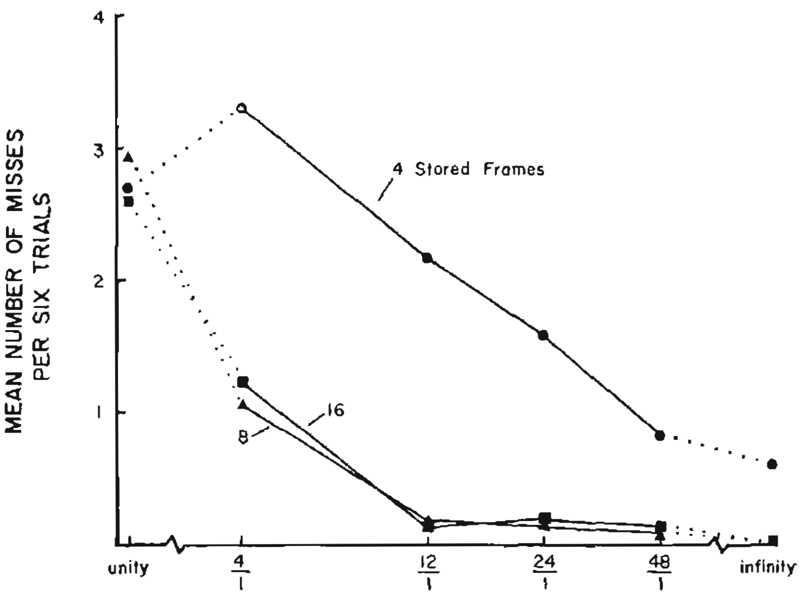


Exhibit 6. Effect of time-compression ratio and number of stored frames on mean number of missed targets per six trials by each of 18 subjects.

been expected based on the subjective appearance of the displays. The infinite time-compression ratio yields a relatively static display that reduces the detection task to one of pattern recognition. On the other hand, the intermediate values of time compression yield both pattern cues and motion cues which should produce superior results.

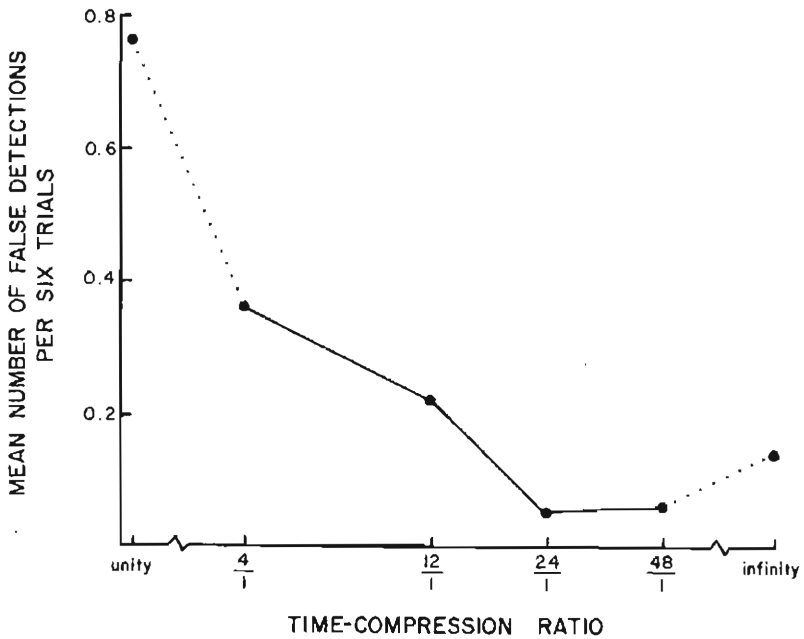


Exhibit 7. Effect of time-compression ratio on mean number of false detections per six trials by each of 18 subjects.

Effects of Variation in Target Characteristics

The effects of target characteristics are of interest because unusual results with a particular target speed or direction could add clues to the understanding of the operation of the perceptual system. For this reason, an additional analysis was performed with target direction and velocity as factors and time to detect as the dependent variable. For two reasons only the data from the last four trials were analyzed. First, a balanced design resulted from the four factorial combinations of two target speeds and two target directions. Had the first two trials been included, a weighted-means analysis would have been required. While this was possible, the first analysis indicated that the error variance was small and that the loss of two trials would not significantly alter the main effects. The second reason for excluding the first two trials involved the possibility of learning effects. It was evident that after the first two trials subjects showed virtually no further improvement.

Once again, time-compression ratio, number of stored frames, and noise level were found to have significant effects ($p < .01$). These results are essentially the same as those found using the means of all six trials as the basis for comparison. Clutter, which had a small but reliable effect in the first analysis, did not show a significant effect during the last four trials. Neither target direction nor target speed had a significant main effect, although several interactions were found to have an effect.

A significant interaction between the number of stored frames and target speed again illustrates the differential effect of 4-frame storage. Up to a time-compression ratio of 12:1, the two different target speeds had little effect on performance with 4-frame storage; for time-compression ratios of 24:1 and 48:1, the difference became relatively large before again becoming small at infinite time compression. This finding provides an additional indication of a change in perceptual effect at the time-compression ratio of 12:1.

DISCUSSION

The data presented clearly support the belief that significant improvement in an observer's ability to detect a target can be realized by matching the display to the observer's perceptual abilities. The data on the number of stored frames indicate that optimum storage lies between 8 and 16 frames, with 10 a likely number. A dramatic increase in performance was found at a time-compression ratio of 12:1, which approximates a playback rate of 100 milliseconds per frame. These two effects and their interaction with one another are among the most interesting in terms of the perceptual process involved.

Exhibit 8 is a simplified plot of the data shown in Exhibit 5. Here the curves for 8-frame and 16-frame storage are combined and approximated by two straight lines. The curve for 4-frame storage is also approximated but with a single line instead of two lines. The abscissa represents playback frame duration, which is equivalent to time-compression ratio when the antenna scan rate is known. Using frame duration, or playback rate, has an advantage in that it is independent of the particular antenna input rate. It has the further advantage of being compatible with measures of perceptual rate used by investigators in other areas of research (Eriksen and Collins, 1967; White, 1963).

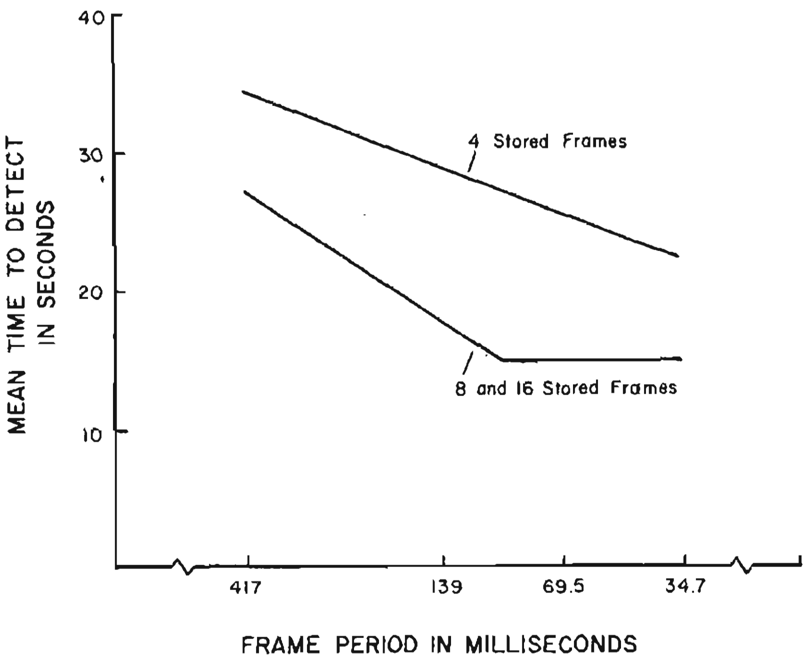


Exhibit 8. A simplified plot of the effect of number of stored frames and playback frame period on time required to detect a target.

Frame Storage

Two characteristics of the relationships shown in Exhibit 8 have evident implications. The first is the effect of 4-frame storage when compared with 8-frame and 16-frame storage. With 4-frame storage, a gradual increase in performance is evidenced as the playback frame period decreases from 417 milliseconds to zero. (Note that the period never really gets to zero but is limited by the frame rate of the TV system which is 60 Hz.) With 8-frame and 16-frame storage, the shape of the function is quite different. This result indicates that input rate affects the perceptual system differently depending upon the number of stored image frames. Four frames of storage are not sufficient to allow apparent motion cues to be fully effective. Under these conditions, increased noise has a large adverse effect on performance. However, comparable noise dependence is not found with 8-frame and 16-frame storage. In fact, in these conditions the effect of noise is minimized, indicating that a time-compressed display with sufficient storage reduces the adverse effects of noise.

Playback Rate

The second characteristic of interest is the abrupt change in performance shown in the lower curve in Exhibit 8. With 8-frame and 16-frame storage, rapid improvement in performance occurs as the playback frame rate approaches a critical value of 100 milliseconds per frame, with little improvement thereafter. This characteristic suggests that beyond this critical frame rate the perceptual system responds most favorably to motion cues. With lower rates, performance is poorer; with higher rates, performance remains approximately the same.

The 100-millisecond value for the critical duration is remarkably close to the critical values found by other researchers. Experiments on perceived simultaneity have generally found that two light flashes appear as simultaneous when separated by less than 80 to 120 milliseconds (Fraisse, 1966; Lichtenstein, 1961). Visual masking phenomena have been observed to occur at interstimulus intervals up to 100 milliseconds. If one visual stimulus is followed within 100 milliseconds by a second stimulus that occupies the same retinal area, the second stimulus will make perception of the first impossible (Eriksen and Spencer, 1969; Kahneman, 1968; Sperling, 1960). Experiments on perceived rate have also demonstrated a dependence on the 100-millisecond duration (Cheatham and White, 1952; 1954; Taubman, 1950; White and Cheatham, 1959).

Although the importance of 100 milliseconds in visual perception is well established, there is little agreement on the reasons for the dependence. One group believes that the effect is due to a fading icon (Neisser, 1967) or decaying visual image (Eriksen and Collins, 1967; Sperling, 1967). The icon sums sensory inputs over a period of time resulting in limited temporal resolution. All encoding and subsequent processing are performed from the trace on the icon. Another group (Stroud, 1955; White, 1963) believes that the perceptual system samples inputs for 100 milliseconds before any processing begins. Therefore, all events occurring within

100 milliseconds of one another appear to be simultaneous. Other theories postulate attention switching mechanisms that require time to change (Kristofferson, 1965; 1966) or gating mechanisms (Mayzner, Tresselt, and Helfer, 1967).

All of these models imply a lack of temporal resolution in the perceptual system consistent with the results of this study; there was a minimal change in performance beyond the 10 Hz playback rate. Although the time-compression ratios of 24:1 and 48:1 were superior to the static multiframe presentations only in terms of their reduced frequencies of false detections, there is ample reason to search for additional differences in future experiments. In this connection, the phenomenal appearance of time-compressed displays deserves comment.

Perceptual Synchronization

Subjects sat approximately 30 inches from the display. At this distance the display could be viewed as a whole, and only a limited visual search was required. When target motion was detected, it was as if the target suddenly appeared in the foreground with the noise receding into the background. The perceptual system seemed to lock onto, or synchronize itself with, the repetition rate of the target and to reject the background noise. This appearance was reported to occur almost without conscious search, which might suggest the existence of a type of coherent movement analyzer in the visual system similar to the feature analyzers postulated for pattern recognition. Such a coherent movement analyzer would have to be highly sensitive to input rate when there are at least eight stored frames, as evidenced by the lower curve in Exhibit 8. However, if a motion analyzer does exist, infinite time compression should suffer from the lack of motion cues.

Target Duty Factor

There may be a methodological reason for the failure to find a consistent difference between infinite and intermediate time-compression ratios. With time-compression ratios other than unity and infinity there is a period of time following the introduction of the target during which returns are present only a fraction of the time. For example, with a time-compressed display with 8-frame storage, when the first target return is received, it will be stored as part of the most recent image frame. As the stored frames are played back one at a time, all but the most recent will contain only noise and clutter, and only the most recent will present the target. In other words, the target will be displayed with a duty factor of only one-eighth. When the second return is received, two frames will contain target information, and the observer can process target returns one-quarter of the time. Continuing this process with four returns, the observer may see the target no more than half the time, and only when eight returns have accumulated can he observe the target all of the time. With 8-frame storage, this means that more than 13 seconds are required before the display can be fully effective. Contrast this with the infinite time-compression ratio in which all available information about the target is presented all of the time. If the target is present only on the four most recent frames, it will appear as four dots that can be observed all of the time.

Spatial and Temporal Integration

The optimum display may be one that combines the advantages of both, namely, the apparent motion cue and the nearly full-time presentation of all available target information. Such a hybrid could be obtained by modifying the playback technique to produce a growing trail. The oldest frame would be displayed, and then the next oldest would be added, leaving the original frame displayed rather than replacing it. Each frame would be added until all stored frames were displayed. Then all frames would be removed, and the sequence would begin again. This would produce a rapidly lengthening line of dots that would have both apparent motion and spatial pattern and would present all available information about the target only slightly less than full time. This most probably would yield a minimum detection time at a playback frame interval in the vicinity of 100 milliseconds.

The data presented clearly demonstrate that superior detection performance can be obtained using a time-compressed display that matches the perceptual system of the operator. These data identify two variables critical to an understanding of the perceptual phenomena involved. These variables are the number of stored image frames and the playback frame rate. The theoretical interpretation of the results is not firm, and a number of possible interpretations are susceptible to future experimental testing.

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