AD A113754

(12)

ENGINEERING-PSYCHOLOGY RESEARCH LABORATORY

University of Illinois at Urbana-Champaign

Technical Report EPL-82-1/ONR-82-1

April, 1982

The Effect of Stimulus-Central Processing-Response Compatibility and Resource Competition on Pilot Performance

Diane L. Sandry

Christopher D. Wickens

Prepared for:
Office of Naval Research
Engineering Psychology Program
Contract No. N-000-14-79-C-0658
Work Unit No. NR 196-158

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER EPL-82-1/ONR-82-1	2. GOVT ACCESSION NO. AD-A113 759	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) The Effect of Stimulus-Central Processing-Response Compatibility and Resource Competition on Pilot Performance		5. TYPE OF REPORT & PERIOD COVERED Technical 6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Diane Sandry Christopher D. Wickens		8. CONTRACT OR GRANT NUMBER(s) N000-14-79-C-0658
9. PERFORMING ORGANIZATION NAME AND ADDRESS University of Illinois Department of Psychology 603 E. Daniel St. Champaign, IL 61820		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS NR 196-158
11. CONTROLLING OFFICE NAME AND ADDRESS Office of Naval Research Eng. Psych. Program 800 N. Quincy St. Arlington, VA 22217		12. REPORT DATE April, 1982 13. NUMBER OF PAGES 60
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release. Distribution unlimited.

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

18. SUPPLEMENTARY NOTES

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

stimulus-response compatibility
resource competition
time-sharing
attention
flight simulation
auditory displays
speech recognition
verbal/spatial

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

The concept of stimulus-central processing-response compatibility is described as a principle by which a task with verbal central-processing components is best served by auditory input and speech response, while a task with spatial processing components is best served by visual input and manual response. A model is proposed that predicts the joint effects of S-C-R compatibility and resource competition when a spatial and verbal task, each paired with all four input/output modality combinations, is time-shared with a visually displayed manual control task.

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE
S/N 0102-014-6601

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE(When Data Entered)

This model was tested in an F-18 flight simulator. Nine subjects time-shared a discrete verbal (communication, navigation, and identification), and spatial (target acquisition) task with the task of flying the simulator through a two-dimensional "tunnel" in the sky. Each discrete task was performed singly with all four i/o combinations, and also concurrently with the flight task. The predictions of the model were upheld. Single task performance on each task benefitted from increasing levels of S-C-R compatibility. In dual task conditions, performance was influenced jointly by compatibility and by resource competition as predicted from the multiple resource model. Furthermore, conditions of high compatibility were uninfluenced by increases in flight task difficulty, while conditions of low compatibility suffered degradation from the difficulty increase. The results of the study suggest that verbal tasks, rather than spatial tasks, will be most benefitted by the use of voice recognition and synthesis technology.

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE(When Data Entered)

The Effect of Stimulus-Central Processing-Response Compatibility and Resource Competition on Pilot Performance

Diane Sandry and Christopher D. Wickens
University of Illinois at Urbana-Champaign

The concept of stimulus-central processing-response compatibility is described as a principle by which a task with verbal central-processing components is best served by auditory input and speech response, while a task with spatial processing components is best served by visual input and manual response. A model is proposed that predicts the joint effects of S-C-R compatibility and resource competition when a spatial and verbal task, each paired with all four input/output modality combinations, is time-shared with a visually displayed manual control task.

This model was tested in an F-18 flight simulator. Nine subjects time-shared a discrete verbal (communication, navigation, and identification), and spatial (target acquisition) task with the task of flying the simulator through a two-dimensional "tunnel" in the sky. Each discrete task was performed singly with all four i/o combinations, and also concurrently with the flight task. The predictions of the model were upheld. Single task performance on each task benefitted from increasing levels of S-C-R compatibility. In dual task conditions, performance was influenced jointly by compatibility and by resource competition as predicted from the multiple resource model. Furthermore, conditions of high compatibility were uninfluenced by increases in flight task difficulty, while conditions of low compatibility suffered degradation from the difficulty increase. The results of the study suggest that verbal tasks, rather than spatial tasks, will be most benefitted by the use of voice recognition and synthesis technology.

Introduction

Auditory Displays and Speech Control

In the high information processing environment of the modern tactical aircraft, auditory display and speech control (A/S) systems offer the potential to capitalize on the best of the operator's communicative abilities and provide him compatibility in unusual circumstances. For example, they are unaffected by weightlessness, and only slightly affected by high acceleration, mild levels of anoxia, and mechanical constraints (Lea, 1978). In addition, the mobility possible with auditory display and speech control is one of its greatest attributes. Speech control enables operation of devices from a distance, from various orientations, and permits simultaneous use of hands and eyes for other tasks. Since voice is familiar to the user, it is normally less difficult to train him to use a speech control system.

Although it seems intuitively obvious to use these alternative channels in complex environments when the visual and manual channels are extremely overloaded, it is not so clear as to how to do so optimally. The speed and range of modern avionics leave little or no room for mistakes in responding to crisis situations. Decision-making in minutes or even seconds is presently essential and is likely to be even more critical in the future with rapid technological advances adding complexity to the cockpit. With little room for error, it is essential that the A/S system not be extensively integrated into system design until basic engineering psychology research has clearly delineated the conditions under which its utilization can produce the maximum benefit to system performance. Careful consideration needs to be given to the nature of a particular task before successful speech implementation can be achieved.

The guidelines for adoption of the A/S system proposed in this report follow from a combination of experimental evidence on dual task performance considered within the framework of multiple resource theory, a consideration of the resource demands imposed upon the pilot of high performance aircraft, and the nature of the tasks he must perform.

Factors Influencing the Advantages and Disadvantages of A/S Channels

The factors that influence the relative advantages or disadvantages of the A/S channels can be assigned to three general categories: (1) unique constraints or limitations on the A/S modalities, (2) the relationship between the input-output (i/o) modalities of a given task and those of competing tasks, and (3) the relationship between the central processing requirements of a task and its i/o modalities. These three factors are important issues for establishing a theory in engineering psychology to provide accurate guidelines for adoption of the A/S system and will be discussed below.

Unique constraints. As a relatively new technology, there exist inevitable limitations in auditory display and speech control capabilities that could hamper information transmission. This is particularly true with regard to speech control, which may be disrupted by voice degradation under situations of stress, be sensitivity to dialect, or to the presence of background noise and distortions. The advantages of speech control are also offset somewhat since at current levels of technological development, a user cannot speak totally naturally, but must insert pauses in between utterances, and must speak within the constraints of the restricted vocabulary of the voice system. In addition, a display or synthesized voice feedback may be necessary for tasks requiring data entry validation. Failure to attend to operator considerations such as microphone mounting, recognition accuracy, error correction, response time and delay, feedback and prompting, and training procedures can have severe implications on system performance (Edman, 1981). The costs, therefore, could outweigh the benefits of speech control capabilities, especially at times other than those of peak workload.

A further limitation is that auditory and vocal channels are by nature serial channels, and therefore may have a more restricted bandwidth than visual and manual channels. Visual signals, for instance, can be simultaneously prolonged for the operator while he manipulates several control devices in parallel. The auditory stimulus in contrast is transient, and of course, only one mouth is available for articulation.

Time-sharing considerations. The second factor deals with the relation between the input/output modalities of a given task and the input/output modalities of a competing task. Ideally, if a visual/manual task is time-shared with an auditory/speech task, perfect time-sharing would occur since there would be no competition for resources. This would predict that cross-modal time-sharing would provide not only better performance than intra-modal, but perfect performance (Shaffer, 1975; Allport, Antonis, & Reynolds, 1972). Realistically however, because a competition for the central processing resources may occur (Treisman & Davies, 1973), or because competition for resources of a "general" nature may exist (Wickens, 1981), independent of whether separate i/o modalities are used, the time-sharing performance may not be "perfect."

It is important to emphasize, however, that time-sharing is normally better with separate i/o modalities than with overlapping ones. Many investigators have demonstrated the advantage of dividing inputs across two modalities (vision and audition) and outputs across two modalities (manual and speech). For example, Fozard, Carr, Tallard, and Erwin (1971) found that subjects searching for a signal (three consecutive letters or digits) in two separate strings of mixed letters and digits performed better when one string was presented auditorily and the other visually than when both strings were presented visually.

Vinge (1972) demonstrated that in a hover control task pilots could best track two displayed functions when one was presented auditorily and the other visually better than two visually displayed functions. Kantowitz and Knight (1976) found that a digit-identification task with a manual response time-shared with a tapping task impaired performance more than with a vocal response. Similarily, McLeod (1977) found that a speech response two-choice tone identification task did not interfere with the simultaneous performance of a tracking task while a manual response did. A more extensive discussion of the time-sharing advantages of the A/S modalities is provided in Vidulich and Wickens (1981).

The increased efficiency of time-sharing tasks with separate input and output modalities can be accounted for within the framework of multiple resource theory. Wickens (1981) has argued that the separate resources may be defined along three dichotomous dimensions: (1) by stages of processing (perceptual/central versus response); (2) by modalities of input (visual versus auditory) and of response (manual versus vocal); and (3) by codes of processing (verbal versus spatial perception and working memory). The response modality dimension is assumed to be highly correlated with the code dimension, given that manual responses are often spatially guided and vocal ones are usually verbal. Wickens (1981) conceptually depicted the "structure" of resources schematically in Figure 1. Within this framework, the greater the extent that two tasks share overlapping resources (common levels on a dimension) the greater will be the interference, and the more changes in the difficulty of one task will be likely to hinder performance of the other. With regard to the A/S dimensions of input and output modalities, Vidulich and Wickens (1981) confirmed both of these assumptions.

The dimension of processing modalities is, of course, critically relevant to the issues addressed in the present research. The dimension of the central processing code, and the manner in which it is related to input and output modality will be critical in describing the

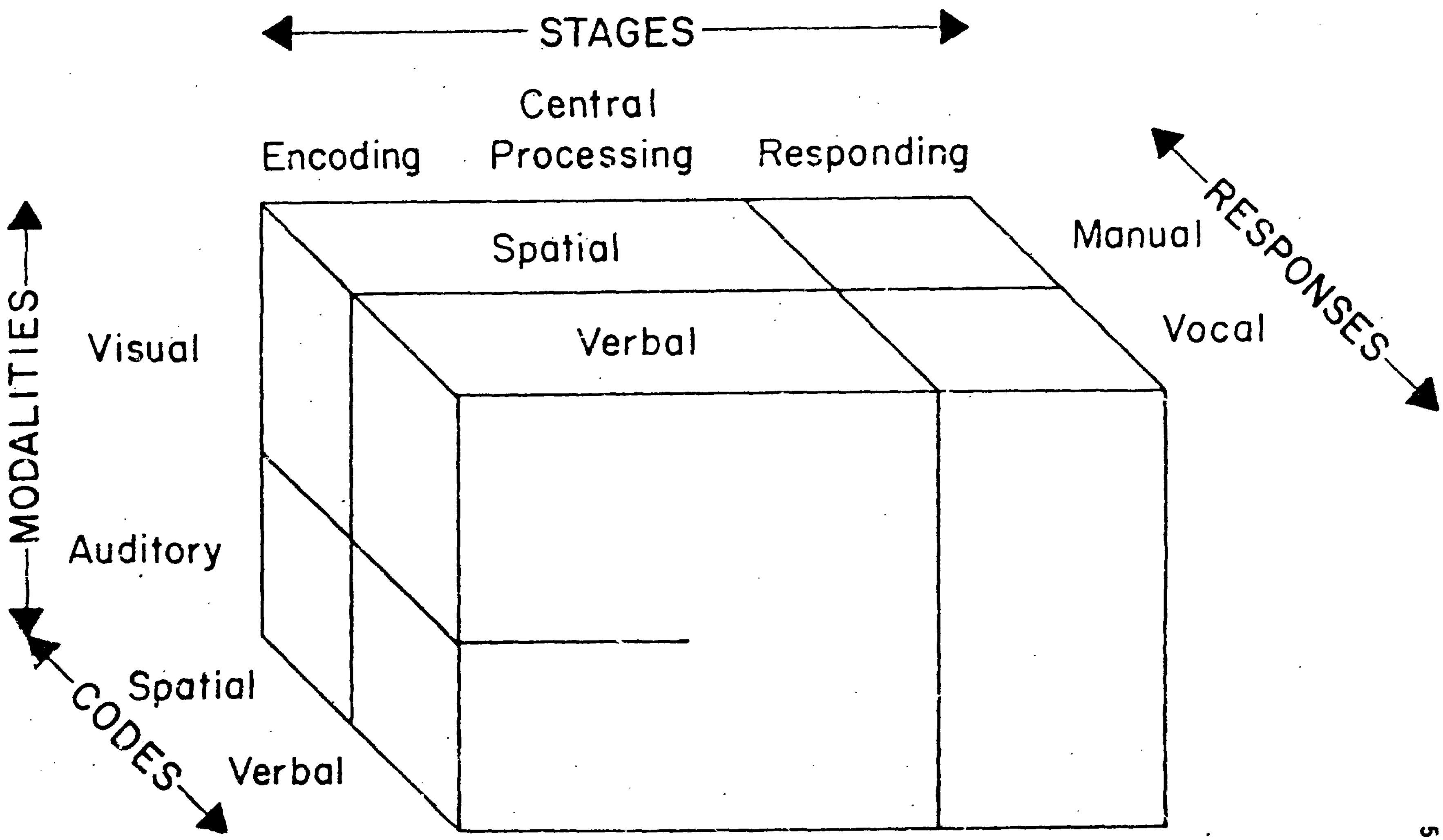


Figure 1. The Structure of Multiple Resources

third potential influence on the use of A/S channels, the issue of S-C-R compatibility.

Single task performance. It is apparent that certain tasks may naturally be suited better for the visual and manual channels than for the auditory and speech ones. Continuous analog control of a dynamic system (i.e., tracking), for instance, appears to be less compatible for speech than for manual control since the speech utterances tend to be discrete, and therefore produce continuous modulation with considerably less precision than does the hand. If the task deals with digits, letters, or words, however, voice, rather than a series of manual responses would appear to be the more efficient means of communication. In the following section we outline a principle of compatibility that defines the optimal relation between central processing demands of a task, and the input/output interface with the human operator.

The Issue of S-C-R Compatibility

The optimal relationship between the central processing requirements of a task and its modality of input and output is based on the underlying concept of stimulus-central processing-response (S-C-R) compatibility. Briefly, we define S-C-R compatibility according to the following two tenets. (1) a taxonomy of the tasks that the pilot must confront reveals that these may be categorized into two groups - those that are predominantly spatial in their central processing demands (e.g., tracking, navigation orientation in space) and those that are predominantly verbal (e.g., communication functions, fault diagnosis, data entry, mental arithmetic). Of course, a number of tasks will require both spatial and verbal processing to various degrees. Some individuals may adopt verbal coding strategies to process spatial information, and vice versus (Umilta, 1978). For example, a pilot designating pertinent geographical locations would be performing a task which was predominantly spatial in nature but contain verbal (name) components; while a pilot entering a way-point (e.g., latitude, longitudinal, elevation) would be performing a predominantly verbal task with some spatial components. It may be best, therefore, to consider that the taxonomy places the task along a spatial-verbal continuum. The more "spatial" or "verbal" a task is, the closer to the ends of the continuum it falls.

(2) It is proposed that there is a unique compatibility relation between codes of central processing (spatial vs. verbal). and modes of input (auditory or visual), and modes of output (speech or manual). S-C-R compatibility is proposed to exist when a verbal task is perceived auditorily and is responded vocally (A/S channels) while a spatial task is perceived visually and responded manually (V/M channels). The benefits of compatibility may be viewed in single task performance but will be enhanced under dual task conditions.

The concept of S-C-R compatibility stems from converging experimental evidence from four related domains: (1) the logic of stimulus-response (S-R) compatibility, (2) the relatively high stimulus-response compatibility found between auditory information and vocal responses, and visual information and manual responses in choice reaction time, (3) the compatibility relation between the hemisphere of initial encoding and the code of central processing, and (4) the corresponding relation between code of central processing and the cerebral hemisphere controlling the response. Each of these components will be briefly considered in turn.

Spatial S-R compatibility. In a series of early investigations Fitts and his colleagues (i.e., Fitts & Seeger, 1953; Fitts & Deininger, 1954) demonstrated that choice-reaction time performance is not solely determined by the stimulus set nor response set, but is instead a function of specific stimulus and response pairings into S-R ensembles. In the compatible situation, where the appropriate motor response is in correspondence with the stimulus, facilitation occurs and reaction times are faster; in the incompatible situation where the response is not spatially associated with the stimulus, interference occurs and reaction times are longer (Wallace, 1971).

S-R compatibility is exemplified in the spatial main and has been shown in several sense modalities. Fitts and Seeger (1953), Fitts and Deininger (1954), and Morin and Grant (1955) demonstrated S-R compatibility with visual stimuli, Broadbent and Gregory (1965) with tactical stimulation, and Simon, Hinrichs, and Craft (1970) with auditory stimuli. Ogden, Anderson, and Rieck (1979) demonstrated that a strong S-R compatibility effect was shown in a dual task setting. Not only were reliable differences in reaction time obtained as a function of the compatibility condition, but significantly fewer choice-reaction time problems were attempted and significantly more errors were made in the incompatible conditions. The effect of lower compatibility was also manifest in degraded performance of the concurrent task, an effect that will be of importance in the present research.

Modality-defined S-R compatibility. There is experimental evidence that compatibility is based upon modality as well. A high stimulus-response compatibility is found in choice reaction time data between auditory information and vocal responses and between visual information and manual response (Teichner & Krebs, 1974; Brainard, Irby, Fitts, & Alluisi, 1962). Brainard, Irby, Fitts, and Alluisi (1962) used auditorily presented numerals and spatially coded lights as stimuli and vocal and manual response codes. As predicted high S-R compatibility was found for numeral-naming (A/S channels) and light-keypressing (V/M channels). If a stimulus was a light, RT was faster for a keypressing (manual) response than for a voice response; in contrast, RT was faster for a naming response if the stimulus was a numeral. Teichner and Krebs (1974) argue on the basis of data summarized across a number of experiments that RT is fastest with a key response to a light and a naming (vocal) response to a digit; as key response to a digit yields an intermediate RT and RT is slowest slowest for a voice response to a light. to a digit yields an intermediate RT.

Shaffer (1975) demonstrated that a skilled typist can successfully type at a high speed from a visual text (V/M channels) while shadowing prose (A/S channels), but has considerably greater difficulty combining typing from an auditory dictation (A/M channels) with reading aloud (V/S channels). Shaffer found that this natural compatibility of input and output modes which was not of critical importance for the two tasks performed singly exerted a greater influence in the dual task conditions. Shaffer's findings appear to be somewhat related to the concept of "ideomotor compatibility" proposed by Greenwald (1972; 1979).

Greenwald (1972, 1979) introduced the concept of "ideomotor compatibility" to describe processing when a stimulus matches the feedback produced by the response. In this circumstance, reaction time will be fast, automatic, and relatively uninfluenced by the number of alternative responses (Greenwald & Shulman, 1973). Thus, when making simultaneous responces to an auditory and a visual stimulus, faster RT will occur when a vocal response is made to the auditory stimulus (i.e., saying a word upon hearing it) and a manual response is made to the visual (i.e., positioning a toggle switch in the same direction as a positioned arrow stimulus), than with the converse assignments. In fact, Greenwald and Shulman (1973) demonstrated that when subjects time-shared two 2-choice tasks, a visual-manual task and an auditory-speech task, there was no time-sharing decrement at all when both tasks were "ideomotor compatible." Shaffer's (1975) finding that subjects could simultaneously type a visual input (visual/manual channels) and shadow an auditory input (auditory/speech channels), but could not perform the converse, is well explained by Greenwald's principle of ideomotor compatibility.

S-C compatibility. The preceding disucssion of S-R compatibility has not explicitly addressed the role of central processing activities in defining compatibility. Theoretical developments in Cognitive Psychology (Baddeley & Hitch, 1975; Wicklegren, 1979; Anderson, 1980; Hammond, 1980), have readily established a dichotomy between two basic codes of information processing--spatial and verbal--at a central processing level. The parallel codes underlie operations of short term memory, transformations of information, and retrieval and storage of information in long term memory. A good deal of experimental data (e.g., Moscovitch, 1979) furthermore suggest that the verbal and spatial codes may be hemispherically related; therefore, it is quite possible that hemispheres of central processing (left-verbal/right-spatial) may underlie some of the compatibility relationships observed. Evidence of such a possibility derives from examples of what may be termed stimulus-central processing (S-C) compatibility and central-response (C-R) compatibility.

Experimental and anatomical evidence suggests that encoding is initially associated exclusively with one hemisphere or the other according to visual field or ear of presentation. Each ear and visual field directly access the contralateral hemisphere. The brain's functional asymmetries dictate some degree of lateralization of central processing activities as well; verbal processes tend to be left hemispherically lateralized and spatial tend to be lateralized in the right. There is a large amount of evidence that the area of the brain responsible for a particular mode of central processing activity offers privileged access to information of that mode that is presented to contralateral perceptual channels (e.g., Moscovitch, 1979; Kimura, 1966, 1969; Geffen, Bradshaw, & Wallace, 1971; Bryden, 1965; Schell & Satz, 1970). We refer to this condition as a state of stimulus-central processing or S-C compatibility. Thus, conditions of S-C compatibility may be induced by presenting spatial information to the left visual field (or left ear), or verbal information to the right visual field (or the right ear).

In addition to the hemispheric laterality relation described above, another manifestation of S-C compatibility is the modality effect of verbal memory research. This refers to a fairly consistent observation that short term memory for verbal material is enhanced when its presentation is auditory rather than visual (Nilsson, Ohlsson, & Ronnberg, 1976; Watkins, 1972; Murdock, 1968). This superior retention of auditorily as opposed to visually presented words hints at a possible "linkage" which may underlie some of the compatibility relationships observed. It should be noted that this observation has considerable practical implications when verbal material is to be presented for temporary storage (i.e., navigational entries presented to the aircraft pilot). Specifically, information presented via auditory channels may be less susceptible to forgetting.

<u>C-R compatibility</u>. When the central processing and response components of a task are associated exclusively with a given cerebral hemisphere (i.e., left hand responds to a spatial task, or right hand or voice responds to a verbal task) a state of C-R compatibility exists. Some investigators have observed superior performance in compatible assignments (Bradshaw & Perriment, 1970), while others have not (Gross, 1972; Alwitt, 1980; Dimond & Beaumont, 1972; Green & Well, 1977). This ambiguity seems to result from the fact that in single task conditions the compatibility benefits of maintaining both functions

within the same hemisphere may be cancelled by a competition for limited information processing resources between processing and response functions within the hemisphere involved.

Recent research suggests that the advantage to C-R compatibility may be strongest in the dual task environment when both hemispheres must utilize processing and response functions under either hand assignment. Under these circumstances no advantage in resource utilization can be gained by distributing response and control centers for a given task across the two hemispheres (Wickens, Mountford, & Schreiner, 1981; Wickens & Sandry, 1980).

Wickens, Mountford, & Schreiner (1981) provided evidence that competition between processing and response within hemispheres is attenuated in the dual task condition. In fact, their evidence suggested a tradeoff of C-R compatibility with resource competition. The investigators observed that time-sharing efficiency between a spatial task (tracking) and a verbal task (digit classification) improved reliably when the spatial task was controlled with the left hand and the verbal was responded with the right hand rather than the converse hand assignment. This emergence of C-R compatibility was labelled "task-hemispheric integrity." The authors proposed that improved efficiency resulted because a given hemisphere handled both the processing and response functions of a given task, and did not have to divide these functions between tasks.

More recently, Wickens and Sandry (1980) replicated and extended the findings of Wickens, Mountford, and Schreiner (1981) in a more carefully controlled series of experiments in which subjects time-shared spatial-verbal and spatial-spatial task pairs, respectively. Specifically, they demonstrated that there is a special advantage to time-sharing efficiency when the hemisphere of processing and response are identical for each task in a time-shared spatial-verbal pair. The dual task integrity effect is abolished when two spatial tasks are time-shared because in these circumstances it is possible for only one task at a time to enjoy a compatible mapping. Wickens, Sandry, and Micalizzi (1981) also firmly established the spatial and verbal, and right and left hemispheric aspects of the tasks that formed the basis of their conclusion.

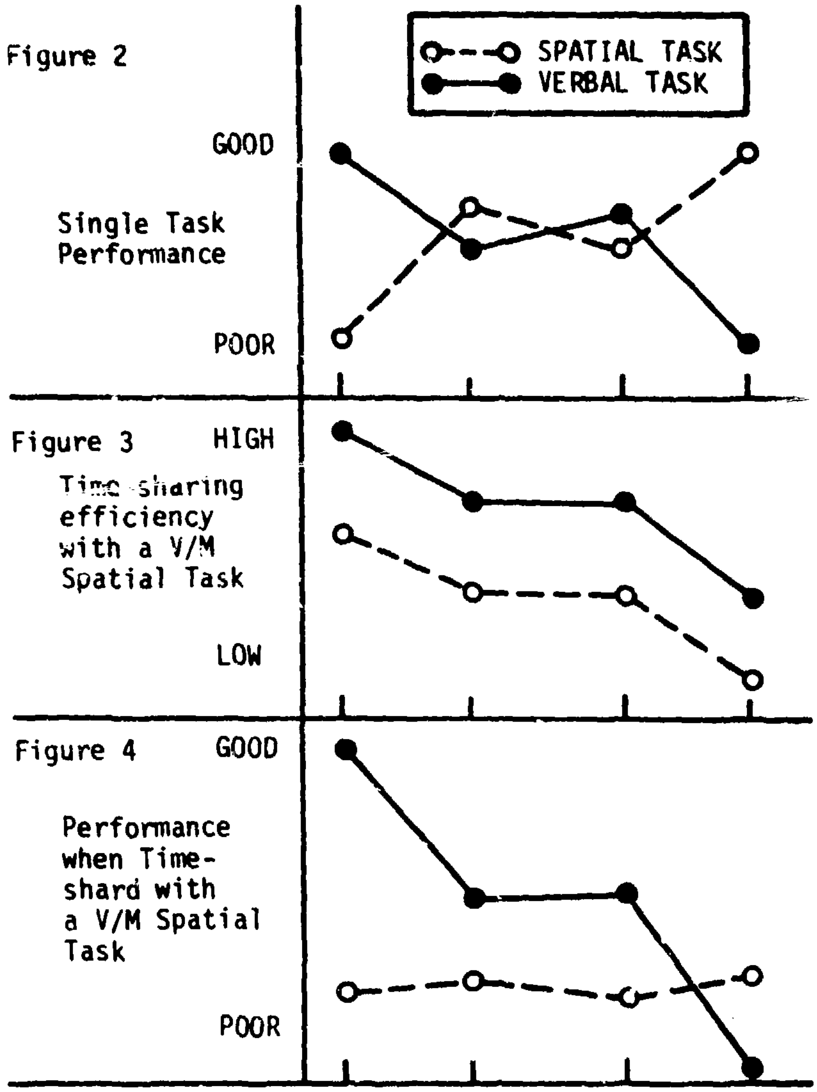
<u>S-C-R compatibility</u>. The concept of S-C-R compatibility integrates the observations of S-R, S-C, and C-R compatibilities. Whereas the study of Wickens and Sandry associated central processing code with response <u>hand</u> (verbal- right, spatial-left) the current development associates processing with response <u>mode</u> (verbal-speech, spatial-manual). In the current discussion, the specific association of the V/M system at encoding and response with the spatial code of

central processing derives from the fairly natural linkages, built up over a lifetime of experience, of the hands and arms with tasks involving visual localization. Correspondingly, the A/S system has typically built up a lifetime of associations with verbal material through comprehension and articulation. It is apparent that other associations exist as well. For example, the visual manual system is also associated with verbal material (reading, writing) and the auditory system has some association with spatial processing (sound localization). It is argued only that these linkages are based upon a lesser degree of world experience than are the spatial-V/M and verbal-A/S associations, and so are less naturally compatible.

Experimental Predictions

Single task. The theoretical predictions of S-C-R compatibility are portrayed in Figure 2 which depicts an idealized relation of the four different input-output modality combinations to single task performance. The input-output modality combinations (from A/S to V/M) are on the abscissa. The ordinate depicts higher levels indicating better performance. Moving from left to right along the abscissa generates increasing levels of S-C-R compatibility and thus increasing performance efficiency for the spatial task and decreasing levels for the verbal. The relative positioning of the four middle points (the V/S and A/M conditions) depends upon the relative importance of preserving or violating S-C or C-R compatibility. For instance, if the verbal task is presented auditorily (the A/M condition) S-C compatibility is maintained; however, if the verbal task is responded to vocally (the V/S condition), then C-R compatibility is maintained. If S-C or C-R compatibility is the more important then performance of the verbal task will be better in the A/M condition or V/S condition, respectively. In the case of the spatial task the converse is true.

Dual task performance: Competition for resources. The time-sharing performance of two tasks is likely to be influenced by the choice of input/output modalities in at least two ways. First, the evidence provided by Wickens and Sandry (1980) suggests that the benefit of an S-C-R compatible mapping will be most effectively realized when there is a heavy time-sharing load imposed upon the operator concurrently engaged in a spatial and verbal task. In the absence of time-sharing requirements it is possible that the benefit of C-R compatibility in particular (e.g., verbal task responded to vocally) may be counteracted by a competition for resources within a given cerebral hemisphere (the verbal processing and vocal response mechanism will both compete for common verbal processing resources, Wickens, 1980). Only when the system is heavily loaded in the first place will the maximum benefit of S-C-R compatible mapping be realized.



Idealized Influence of I/O Modality on Single Task Performance (Fig. 2), Dual Task Time-sharing Efficiency (Fig. 3), and Total Dual Task Performance (Fig. 4), when a Spatial & Verbal Task is Time-shared with Flight Control.

Second, the logic of multiple resource theory (Navon & Gopher, 1979; Wickens, 1980) predicts that interference between tasks will be an increasing function of the degree of overlap of input and output modalities between the primary and secondary tasks.

An investigation by Wickens and Harris (Wickens, 1980), in which a tracking task (V/M) was paired with a discrete verbal task employing all combinations of input and output modalities suggested that task interference was a roughly additive combination of overlap of input and output modalities. Somewhat similar results were also obtained by Vidulich and Wickens (1981), althougn there were asymmetric patterns of interference between the tracking and discrete task. Figure 3 depicts an idealized relation of input-output competition on the interference resulting from time-sharing two tasks. In order to preserve the relationship of Figure 2, in which good performance is up, the hypothetical data in Figure 3 are plotted in terms of time-sharing efficiency, the reciprocal, or negative of task interference. All input-output combinations (from A/S to V/M) are on the abscissa. The ordinate, moving from left to right, generates decreasing time-sharing efficiency with the spatial V/M primary task (e.g., a tracking or flight control task).

The shape of the function shown in Figure 3 depends upon the relative importance of perception vs. response in the tasks involved. If both tasks are heavily perceptual, for example, the efficiency of the two versions sharing common input (V/M and V/S) will be lowered relative to the two versions sharing common output (VM and AM). The overall level of time-sharing efficiency, the height of the function, will depend upon the degree of overlap of central processing demands. Since spatial and verbal processes seemingly define partially separate resources, two spatial or two verbal tasks will show a greater level of mutual interference and therefore lower time-sharing efficiency than will a spatial and verbal task (Wickens, 1980). This difference is reflected in the lower "intercept" of the spatial task. Note finally that the curves may represent the efficiency of either or both tasks. A resource model assumes that competition may be reflected into either task according to the resource allocation strategies adopted by the operator (Wickens, 1981).

Absolute level of dual task performance. Naturally, the measure of most importance to the system designer is neither the level of single task performance nor the magnitude of a relative dual task decrement, but the absolute level of dual task performance. Conceptually, this is equal to the additive combination of Figures 2 and 3. If we assume that a primary task is spatial with V/M modalities (e.g., the manual control task usually confronted by the pilot) and a secondary task of either spatial or verbal processing is performed concurrently using all input/output combinations, then Figure 4 presents the predicted level of dual task performance generated by aggregating the hypothetical data of Figures 2 and 3. The ordinate, moving from left to right, generates decreasing time-sharing efficiency with the V/M primary task. At the same time, it generates increasing S-C-R compatibility for a spatial secondary task. Thus, the two trends roughly "cancel" each other and dual task performance will be predicted to be relatively insensitive to i/o modalities. On the contrary, for the verbal secondary task, movement along the ordinate generates conditions both of increasing i/o overlap and lower S-C-R compatibility. The trends reinforce each other and the performance function drops steeply. The overall level of spatial task performance is diminished relative to verbal because of the competition between tasks at the central processing level, for spatial resources.

Naturally, the precise shapes cannot be predicted exactly. Whenever we predict the opposing influences of two factors (as between S-C and C-R compatibility, or between S-C-R compatibility and interference in the spatial task), the precise shape of the combined function will be determined by the relative magnitude of the two influences. The major prediction that can be made is that S-C-R compatibility will have more of an influence on the verbal than the spatial central processing tasks.

The present experiment sets out to test this prediction in a scenario that maintains a considerable degree of fidelity to the pilot's tasks. The primary task is a terrain avoidance flight path flown on an F-18 simulator. (The term "primary" is used to describe the flight task not as an indicator of the specific instructions provided to the subjects, but rather to indicate the primacy of flight control in general.) A spatial and verbal discrete task involves, respectively, (1) a task of target localization achieved by slewing a cursor to the designated one of three targets, and (2) a series of communication, navigation, and identification (CNI) commands requiring data storage and entry. Each of these is paired in turn with the primary task at two difficulty levels, and all input-output combinations of each secondary task are generated.

Method

Subjects

Ten right-handed male subjects participated on a voluntary basis. All subjects were employed at the Naval Air Test Center (NATC), Patuxent, River, Maryland, had normal to corrected to normal vision, and ranged in age from 22 to 46, with an average age of 30. Subjects had an average of nine years of flight experience and were screened to ensure that at minimum they were certified single engine airplane pilots. None of the ten subjects had seen, used, or studied the F/A-18 simulator. Right-handed male subjects were used because hemispheric specialization is most consistent in right-handed subjects (Gross, 1972). The degree of right-handedness was also evaluated for each subject using inventories developed by Bryden (1977) and by Crovitz and Zener (1962) (see Appendices A and B, respectively).

Apparatus

System architecture. Each subject performed the tasks on the F/A-18 simulator (see Figure 5), a general purpose simulation system designed to provide a test platform for flight avionics hardware and software. The five mission computers in the F/A-18 coordinate and control the flow of information between the avionics subsystems and the pilot. Real time three dimensional graphics is provided by an Evans and Sutherland picture system II (PSII) display processor which generates a cockpit view "out the front window." A microprogrammable two dimensional display processor (Adage 4195) provides for special high speed graphics.

Operator station. The visual stimuli of the three tasks (terrain-avoidance flight, target localization, and CNI) were displayed slightly above eye level on a 30 x 32 cm head-up display (HUD) screen located on the main instrument panel. Auditory stimuli were presented through AKG-K240 earphones. Subject's responses from the control stick, control button, and up front control panel (UFC) were processed, and a PDP mini-computer recorded subject performance for later analysis. The computer system was interfaced with a VOTERM voice recognition system in order to record performance data during the vocal response condition. Speech responses were articulated into a microphone mounted to the headset and positioned near the subject's mouth.

The subjects were seated in a sound and light attenuated room directly in front of the main instrument panel facing the HUD screen. When positioned correctly, the subjects' eyes were approximately 75 cm from the HUD. The distance of the chair to controls was adjusted according to the length of the subjects' arm. The control stick (for the flight task) was a spring-loaded dual-axis hand control operated with the right hand for control of pitch and bank angle. A spring-centered, circular, push-button finger control located on the throttle was operated with the index finger of the other hand for the target localization task. The UFC panel (for the CNI task), positioned directly below the HUD, consisted of a keyboard, a set of function switches, a scratchpad readout, and a set of options display windows with corresponding option select switches.

Figure 5: View of Subject Experimental Configuration.

UFC panel. The UFC panel, used for manual interaction with the verbal task, is shown in Figure 6. The keyboard on the UFC consists of twelve 1 cm push-button keys in a four row-three column configuration numbered one through nine with the last row containing a "clear" button, a "zero", and an "enter" button. In addition, the directions north, west, east, and south are assigned to buttons numbered two, four, six, and eight, respectively. A horizontal row of seven 1 cm push-buttons form the set of function selection switches across the bottom of the UFC. From left to right the switches read auto-pilot (A/P), identify friend or foe (IFF), tacan (TCN), instrument landing systems (ILS), data-link (D/L), radar beacon (BCN) and on/off. A scratchpad readout across the top of the UFC gives visual feedback of the input. From the set of five vertical option display windows and corresponding option select switches along the right side of the UFC, only the top three windows are used for longitude, latitude, and elevation, respectively.

Voice recognition system. The VOTERM voice recognition system used was a speaker-dependent, isolated-word recognizer which automatically recognized spoken words or phrases. These words or phrases were called utterances and had to be in the range of 0.1 - 2.0 seconds in duration and separated by short pauses of 0.15 seconds or more. A speech preprocessor determined the beginning and ending of each utterance.

During the training mode the subjects were given a numbered list of thirty-six words. A "prompt" (associated with each word) was displayed on a CRT terminal to notify the user of the word to be trained. For example, the prompt "say word 1" required subjects to reply "IFF." The experiment required eight to twelve passes through the vocabulary list for most subjects.

Two types of errors occurred: misrecognition and rejection. Misrecognition errors occurred when an output string was selected that did not match the utterance. Rejection errors occurred when the system rejected the utterance as not part of the vocabulary. In the latter case the subject was signaled with a tone. Most often error was due to operator failure such as word mispronunciation, use of a word not in the vocabulary, or a word spoken too fast or too slow.

Task Description

Terrain-avoidance flight task. The main task was a terrain-avoidance flight path which required flight through a contrived corridor (or tunnel) displayed on the HUD screen. The corridor was a

ELECTRONIC EQUIPMENT CONTROL

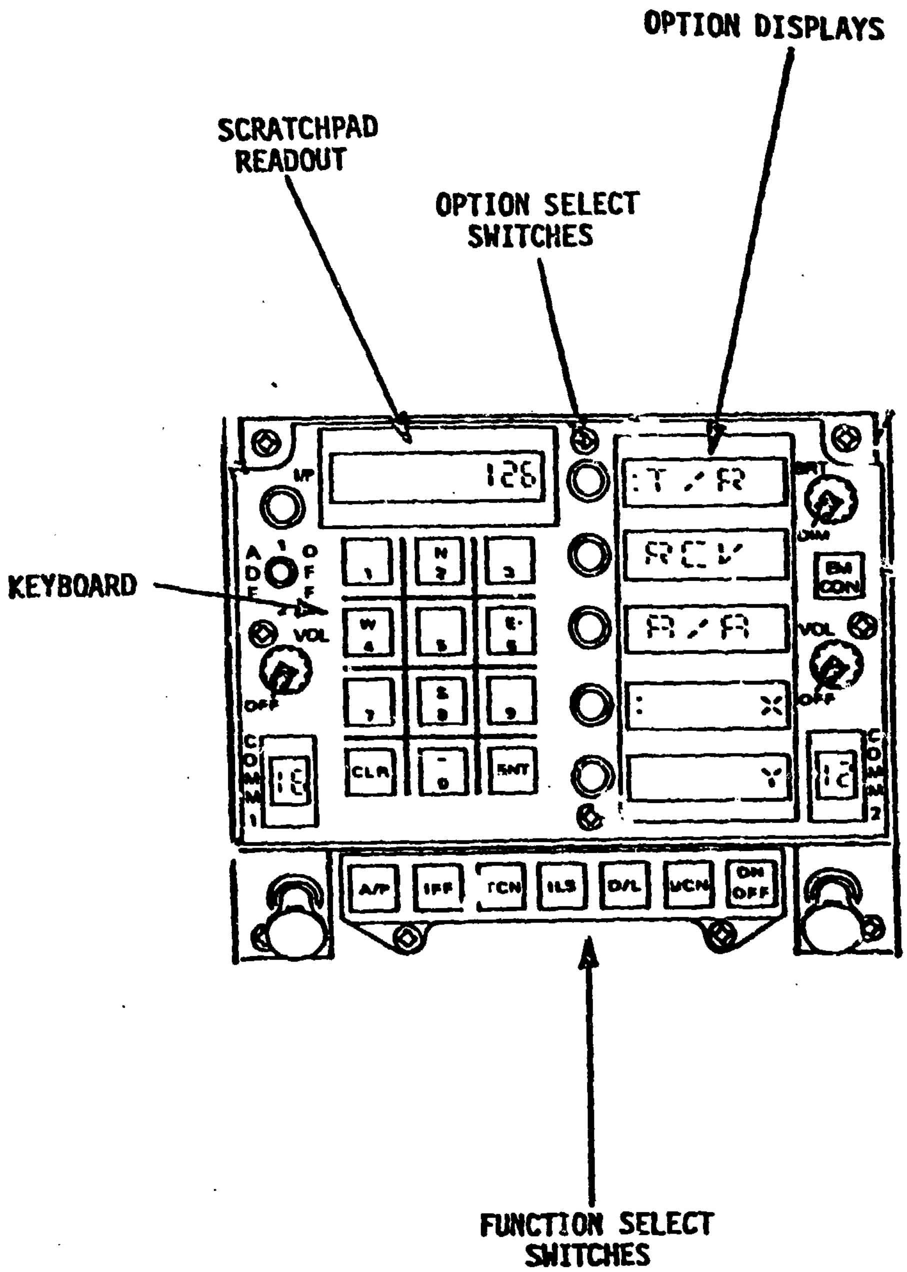


Figure 6: Up Front Control Panel.

three-dimensional figure describing the trajectory the pilot had to follow. Its cross-section was rectangular, a simulated 600 feet wide and 150 feet high. Perfect performance entailed a complete flight along the invisible longitudinal axis of the tunnel, around which the rectangles were circumscribed. The tunnel had a serpentine appearance which represented the terrain-avoidance task. Corridors were randomly generated and each was carefully analyzed (e.g., for dips, turns, inclines, etc.) and rated for difficulty. Twelve distinct but equally difficult tunnels were chosen for the main task and were presented to the subjects randomly. Figure 7 shows an example of one such tunnel. In this figure the pilot is flying off course, well to the right and above the desired flight path. Each flight lasted approximately 4 minutes. Two levels of task difficulty were used, defined by flight velocity. The "easy" condition required subjects to maintain a flight velocity of 300 knots and the "hard" condition required 500 knots. This difficulty variable was analogous to the manipulation of the bandwidth of command input in a laboratory tracking task since the higher velocity required a higher frequency of corrections. The basic flight data were presented on the HUD as shown in Figure 8.

The simulated pitch and roll dynamics approximated those of an F/A-18 aircraft. Each axis was of first-order with an exponential lag. Primary task tracking performance was summarized by a figure of merit (FOM), which was a weighted index that accounted for horizontal and vertical error and air speed. The FOM equaled the air speed (in knots) divided by the weighted RMS error. In the calculation of the RMS error, subjects were penalized four times more for vertical deviations from the central-axis than for horizontal deviations. In addition, the penalty was a linear function of the distance from the central-axis to the edge of the rectangle. From the edge of the rectangle-out the penalty became an X^2 function.

Verbal CNI task. Three epochs of the verbal task were presented at semi-random times during a flight trial. The first epoch randomly occurred during the first third of the trial, the second during the second third, and the third during the final third. Each epoch contained a command which was drawn from the communications, navigation, and identification package of the system and was presented either visually across the bottom of the HUD (see Figure 9) or auditorily through headphones. A typical trial might consist of the following three commands: (1) squawk ident 1347, (2) enter latitude north 2142, and (3) turn on radar-beacon, tacan, ith - which would then be assigned a scenario number. Twenty-four such scenarios were generated (see Appendix C) and were randomly presented within and across all subjects. Manual responses were performed on the UFC and vocal responses were performed via the VOTERM. The number of steps required to complete each task were identical in both the visual and manual modes. For instance, to "squawk ident 1347" manually, subjects

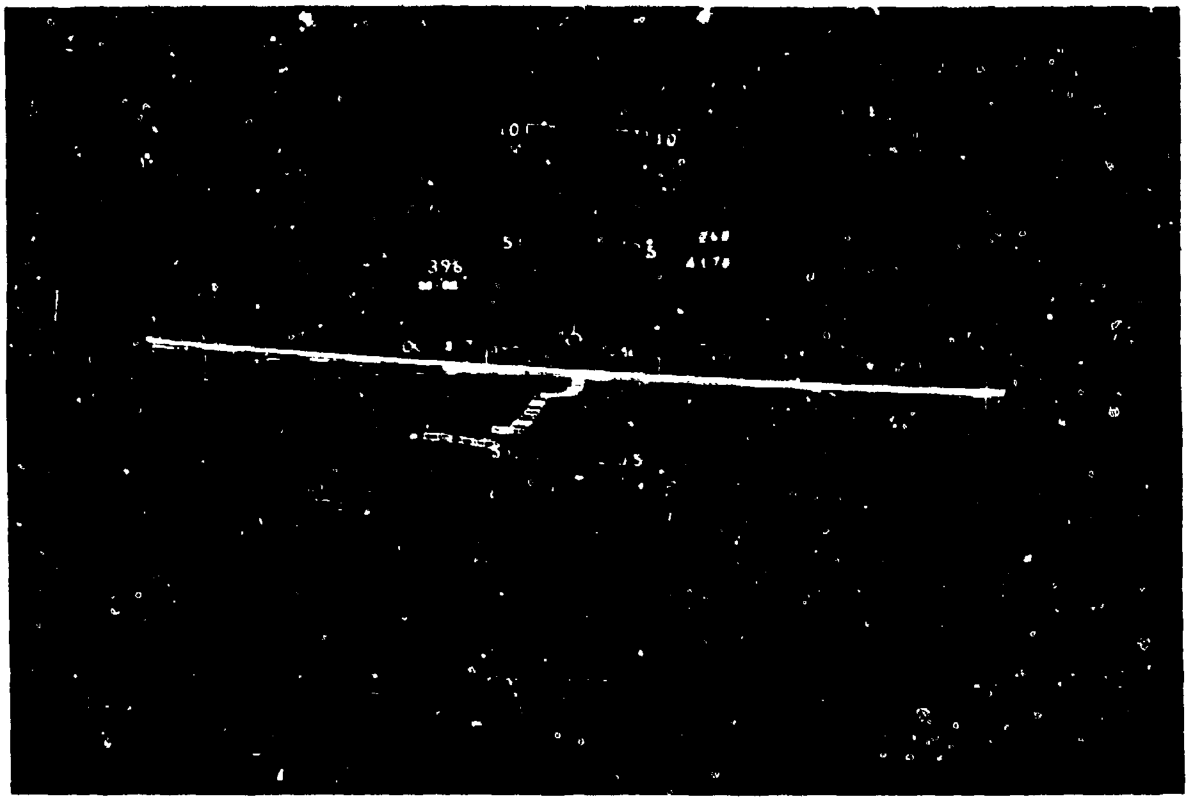
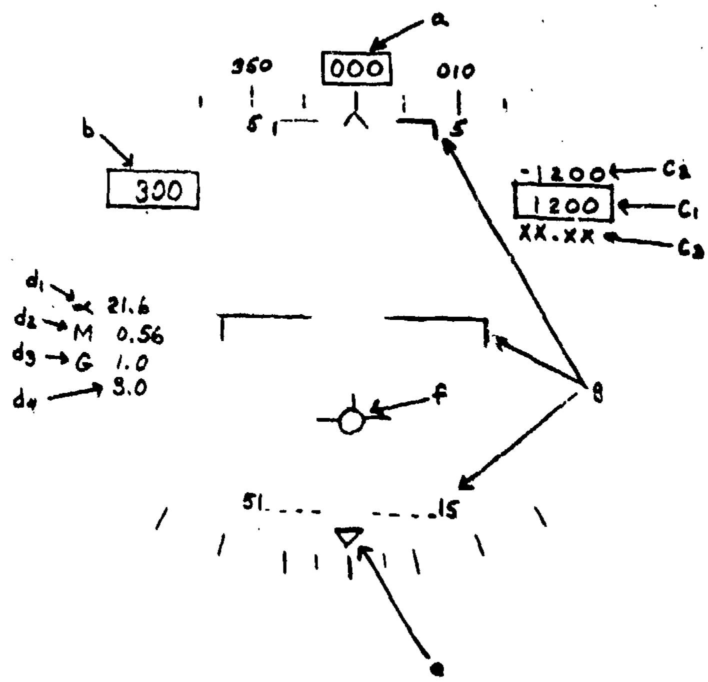


Figure 7. The Primary Flight Task.



HUD Basic Flight Data

a) heading
b) air speed
c_1) altitude
c_2) rate of climb/descent
c_3) barometric setting
d_1) angle of attack
d_2) mach number
d_3) aircraft G's
d_4) peak aircraft G's
e) bank angle scale
f) velocity vector
g) flight path/pitch ladder

Figure 8: Basic Flight Data Presented on the Heads Up Display.

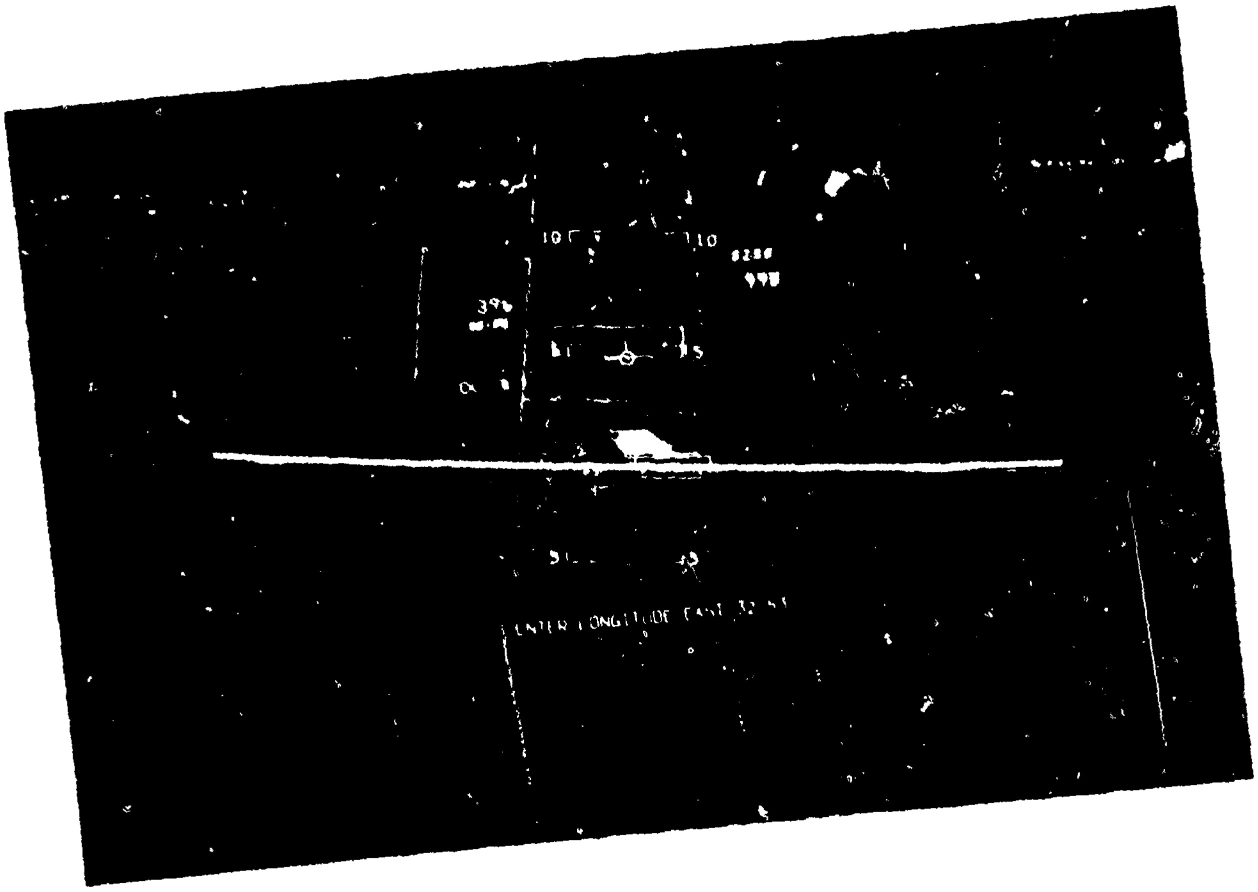


Figure 9. The Primary Flight Task (pilot is in the tunnel) with the Visual-Verbal Secondary Task Display.

performed a series of four steps: (1) pushed the IFF button, (2) entered the digits 1, 3, 4, and 7, (3) checked on the readout for accuracy, and if the readout was correct (4) pushed the "enter" button. If the readout was incorrect, subjects cleared the panel and re-entered their correction before the "enter" button was pushed. Verbally, subjects commanded (1) "IFF", (2) "1", "3", "4", "7", (3) subjects checked the readout, and if correct, (4) subjects commanded "enter." In both response modes the readout was displayed visually and could not be changed once the "enter" mechanism was activated. Subjects had forty seconds to successfully complete a task, after which they timed-out.

Each subject was told to respond as rapidly as possible, while maintaining a low error rate. Reaction time (RT) and error percentage were recorded as performance measures. Response latency was measured from the appearance of the visual string, or the termination of the final auditory command, to the initiation (or recognition in the speech condition) of the "enter" command. Subjects' responses were rated correct, incorrect, or timed-out.

Spatial target-localization task. A single trial of the spatial task, like the verbal task, consisted of three epochs. A stimulus command was presented (auditorily via headphones, or visually across the bottom of the HUD screen) that designated the identity of the one of three target stimuli to be localized. These stimuli appeared on the HUD screen below the tunnel. For instance, during the first epoch, pictured in Figure 10, the aircraft approached a factory (on the left), a hangar (middle), and a group of houses (right). When commanded to "designate" one of the three targets, the subjects slewed the circular cursor (seen at the center of Figure 10) to the appropriate target (either manually or vocally) and designated it, receiving visual feedback for correct localization. The pilot's task, then, was to select and designate the correct target as rapidly as possible while maintaining a low error rate. Manually, the pilot located the correct target by slewing the cursor to the center of the appropriate point using the spring-centered dual-axis finger-button located on the throttle. The control dynamics of this task were pure rate control. Once the subject correctly located the target and appropriately designated it (by pressing the spring-centered button), the target vanished, thereby indicating a correct response.

In the speech version of the task, subjects slewed the cursor to the appropriate point by commanding clock-like directions. A command of "two-o'clock" for instance, moved the cursor at a constant velocity up and to the right (the two-o'clock position on the clock). The velocity of motion was equivalent to the maximum velocity available with full stick deflection in the manual condition. Since the full deflection was normally employed by subjects in the latter condition,

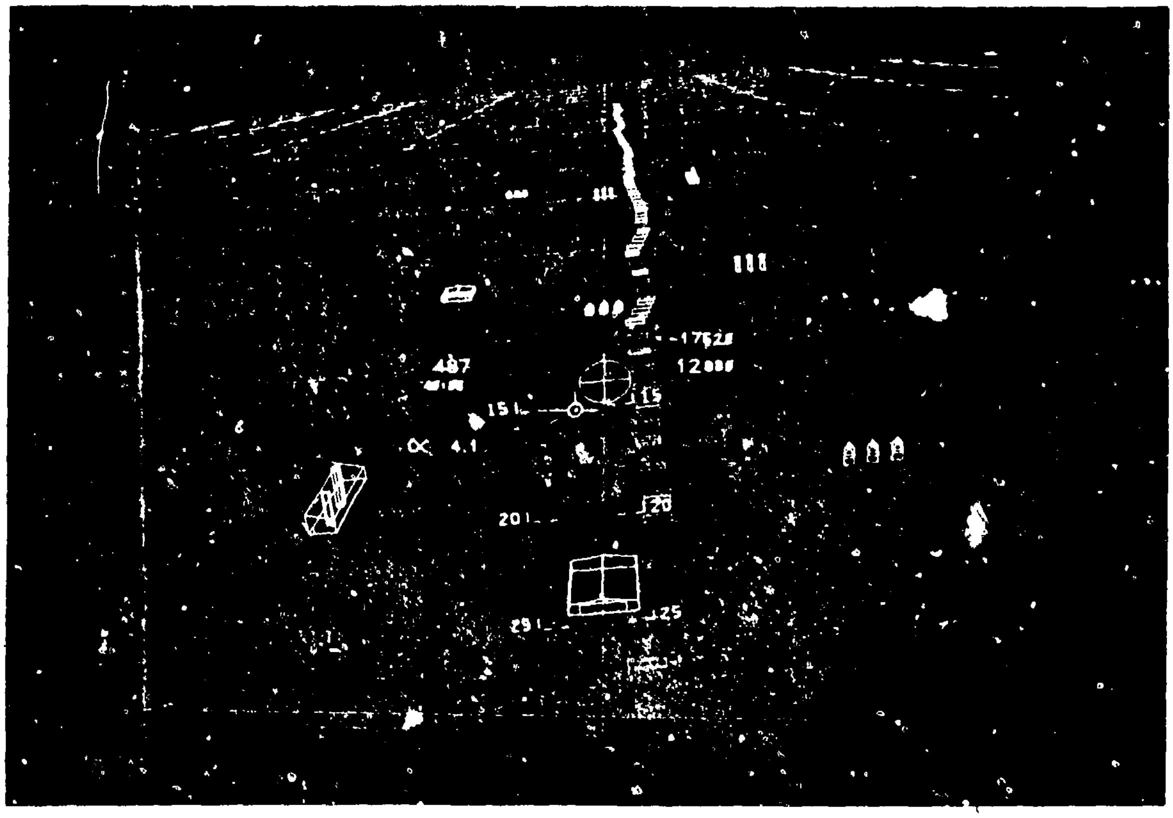


Figure 10. Primary Flight Task with Spatial Discrete Task Display.

there was little difference in the physical control strategy adopted by subjects in the two response modes. In addition, the cursor was stopped, or reset in its original position, or designated with the commands "stop", "reset", and "designate", respectively.

Twenty-four scenarios were generated. Each consisted of three targets in different random positions and the designation assignment. The twenty-four scenarios were randomly presented within and across all subjects. Reaction time and error percentage were recorded as performance measures. Subjects had forty seconds to successfully complete a task before they timed-out.

Design

A within subject design was employed in which each subject participated in all experimental manipulations. The data of two subjects was discarded due to the disruption of correct procedure resulting from computer failure. Sessions lasted approximately two hours and took place on "near-to-consecutive" days. The first 2-3 sessions (approximately 4-6 hours) were used to train the subjects to fly the F/A-18 simulator. A subject had to meet a pre-specified flight criterion measure in order to participate further. The measure required subjects consistently to keep a minimum of 80% of their flight within the rectangle boundaries of the flight path under both 300 and 500 knot difficulty conditions. All subjects met the criterion within six practice hours. The fourth session was used to train subjects on the voice recognition system and to familiarize them with single spatial and verbal task performance. Only after subjects could proficiently perform the single flight task and the single side tasks (using both modes of input and output) were they trained in dual tasking pairings. Sessions five and six (approximately 4 hours) were used for the dual task training. By the end of the sixth session subjects were trained in all experimental manipulations. The next six - 2 hour sessions were used to collect data.

The orthogonal combination of two encoding modalities and two response modalities generated four input-output modes designated AS, AM, VS, and VM (the first letter defining the mode of input, the second the mode of response) for each of the two side tasks, which formed eight single task conditions. The flight task was performed at two levels defined by task load (2 single task conditions). The two side tasks were each paired with the flight task, which formed 16 dual task pairs. The design, therefore, generates 26 conditions (16 dual, 10 single), which are schematically diagrammed in Figure 11. Subjects performed the 26 conditions in random order during each session. The 26 conditions, therefore, were replicated six times and were randomized within and across all subjects.

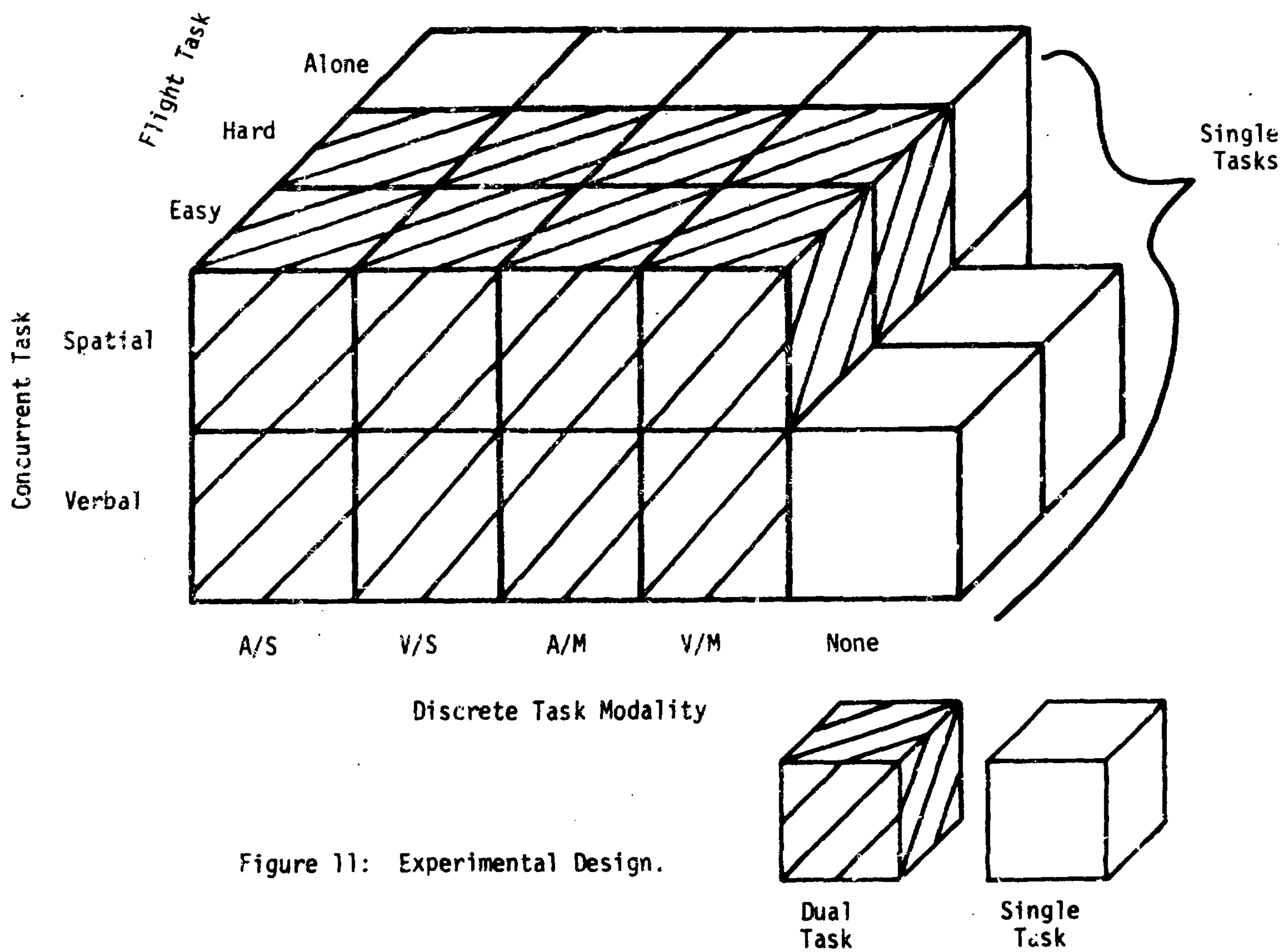


Figure 11: Experimental Design.

Procedure

Prior to data collection, subjects filled out a general personal-data form and the two questionnaires of handedness. Subjects then participated in 12 sessions (2 hours each) of training and data collection. Prior to the presentation of a trial, the subject was informed of the task to be performed and was instructed when the trial was to begin. On the spatial and verbal tasks, subjects were instructed to perform the tasks as rapidly as possible while keeping their error rate low. On dual task trials, subjects were told to divide their attention as evenly as possible between the two tasks, and that under no circumstances should they respond entirely to one task while ignoring the other.

Midway through each session, subjects were allowed a 15 minute rest period. At the completion of data collection, subjects filled out a subjective questionnaire asking them to rate preferences of input-output modes and difficulties of the tasks involved.

Results

Single Task Analysis

Primary flight task. Statistical analysis of the FOM error data was accomplished with a 3-way (subject x level x replication) analysis of variance. The mean FOM error was 3.015 for the easy level (300 knots) and 2.991 for the difficult level (500 knots). The analysis of variance showed that the difference between mean FOMs of the two levels, essentially a change in the tracking bandwidth, was not statistically reliable ($F(1.7)$) = 0.711, $p > .05$). Although there was no reliable difference in how well subjects performed the two versions of the task under single task conditions, it can be confidently asserted that the difficulty was, in fact, harder for the faster speed because subjects subjectively rated it so. Further differences between the easy and hard level were revealed when the secondary task was imposed, as will be reported below.

Discrete tasks. Statistical analysis of the single task data was accomplished using a 5-way (task x subject x input x output x replication) analysis of variance. The data, plotted in Figure 12, task latency (seconds), for the two tasks (spatial and verbal) across the four different input-output modality combinations (A/S, V/S, A/M, V/M). In keeping with the uniform representation that good performance is up, the data are plotted in such a way that long reaction latencies, (poor performance), are near the origin. Error rates for the discrete tasks are shown in parentheses. Since these are generally low, and correlated positively with latency, differences in latency between conditions are not apparently the result of a speed-accuracy tradeoff (Pachella, 1974).

The compatibility effect predicts that moving from left to right along the abscissa in Figure 12 generates increasing levels of S-C-R compatibility and therefore increasing performance efficiency for the spatial task and decreasing levels for the verbal. These predictions are both generally confirmed by the data. The positioning of the four middle points (in which C-R compatibility was pitted against S-C compatibility) shows a main effect for C-R compatibility: conditions of C-R compatibility (i.e., the A/M condition for the spatial task, the V/S condition for the verbal) yielded better performance than did the conditions of S-C compatibility in either of the two tasks.

Across both tasks the input was reliably faster than the visual ($F(1,7) = 15.85$, $p < .01$). This finding may be an artifact of the timing mechanism in the study for auditory input. The timing began at the end of the auditory utterance. If subjects began to process information before the end of the utterance, then this timing logic would tend to underestimate the time required by the pilots to process the auditory cues, relative to the visual condition, in which timing and information availability both start simultaneously.

The different trends of the two tasks shown in Figure 12 are substantiated by the analysis of the interactions between task and modality. The task x input interaction was found to be statistically significant ($F(1,7) = 89.43$, $p < .0001$). For the spatial task, the mean RT for visual input (8.05) was faster than the mean RT for auditory (8.55). In contrast, for the verbal task, the mean RT for the auditory input (7.60) was faster than that for the visual (9.15). A reliable task x output interaction was also found in the direction supporting the C-R compatibility concept. ($F(1,7) = 48.28$, $p < .001$). For the spatial task, the manual mean RT (7.30) was faster than the vocal (7.30), while for the verbal task the relation was reversed.

The main effect of task was not statistically reliable ($F(1,7) = .017$, $p > .05$), thereby confirming that in the single task condition the two secondary tasks (spatial and verbal) were of equal difficulty. In addition, the 3-way interaction of input modality by output modality by task was not reliable ($F(1,7) = .055$, $p > .05$).

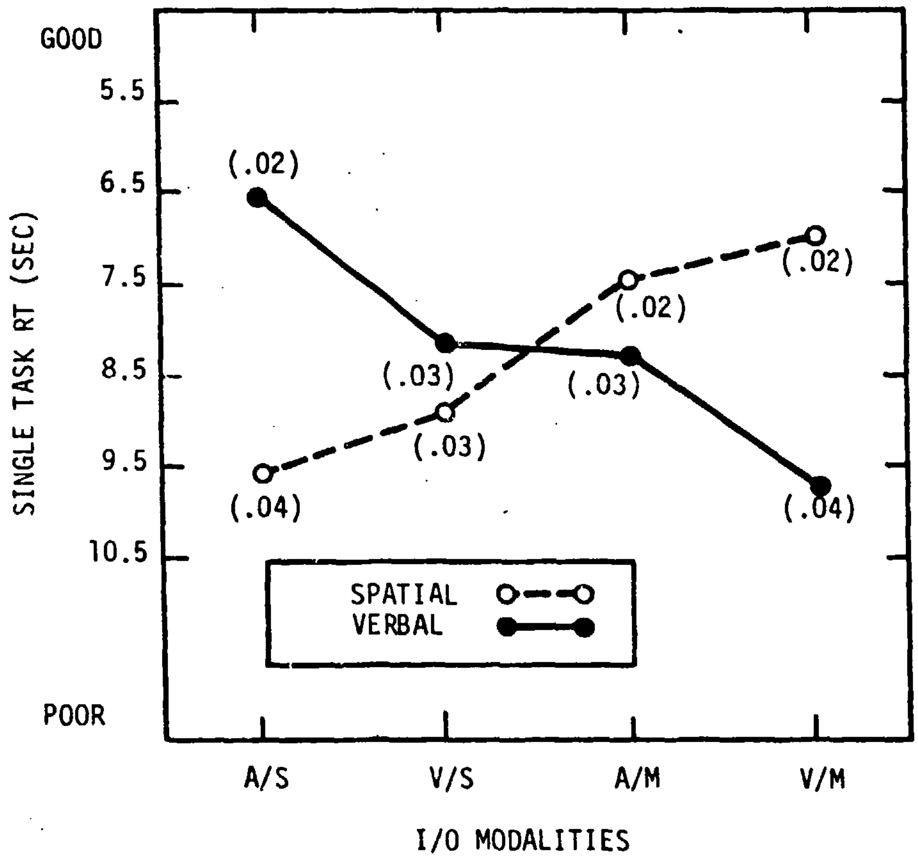


Figure 12: Single Task Performance Speed for the Verbal & Spatial Tasks.

Dual Task Analysis

Two aspects of the dual task results are relevant: (1) time-sharing efficiency as revealed by the analysis of decrement scores from single to dual task conditions, and (2) the absolute level of dual task performance. Both of these may be interpreted in terms of performance on either task or a combination of both. Hardware-induced timing differences between the two modes of input (i.e., RT began at the offset of the auditory stimulus rather than the onset) and between the modes of output (e.g., a speech response was accepted at the time of system recognition, not onset or offset of voice) complicated the interpretation of both single and dual task performance on the discrete tasks when the main effects of input and output modes are considered. Initially, therefore, the dual task decrement scores will be discussed. These effects should be free of any artifacts due to timing, since these artifacts, potentially present in both single and dual task data, will be subtracted out when decrements are considered.

The dual task data, response latencies of the discrete task and the figure of merit or FOM of the flight task were transformed to decrement scores by subtracting the corresponding single task performance measure. For the discrete tasks, the single task RTs were subtracted from the obtained dual. The flight task consisted of three phases (pre, during, post) that were temporally mutually exclusive and exhaustive. The "pre" stage occurred before the secondary task presentation and was therefore, a stage of single task flight. The "during" was the time in which the pilot was presented with the secondary task and was required to respond. The "post" was a fixed time interval which occurred immediately after the secondary task completion and was a "recovery time", in that it allowed the pilot time to return the aircraft to stable flight before the next "pre" phase. The decrement scores for the flight task, therefore, were calculated by subtracting the FOM pre from the FOM during (that is, dual task minus single task). This produces a measure of time-sharing efficiency.

Flight task time-sharing efficiency. Figure 13 presents the measure of flight task time-sharing efficiency for the FOM. Compared to the hypothetical data in Figure 3, the two functions each follow relatively close to the predicted outcomes. The verbal task function (solid line) and the spatial task function (dashed line) each portray the result of incremental decreases in performance with increases in input-output overlap from A/S to V/M, and the overall level of efficiency for the spatial task is lower. The four middle points indicate that input and output competition exert roughly equal effects on efficiency.

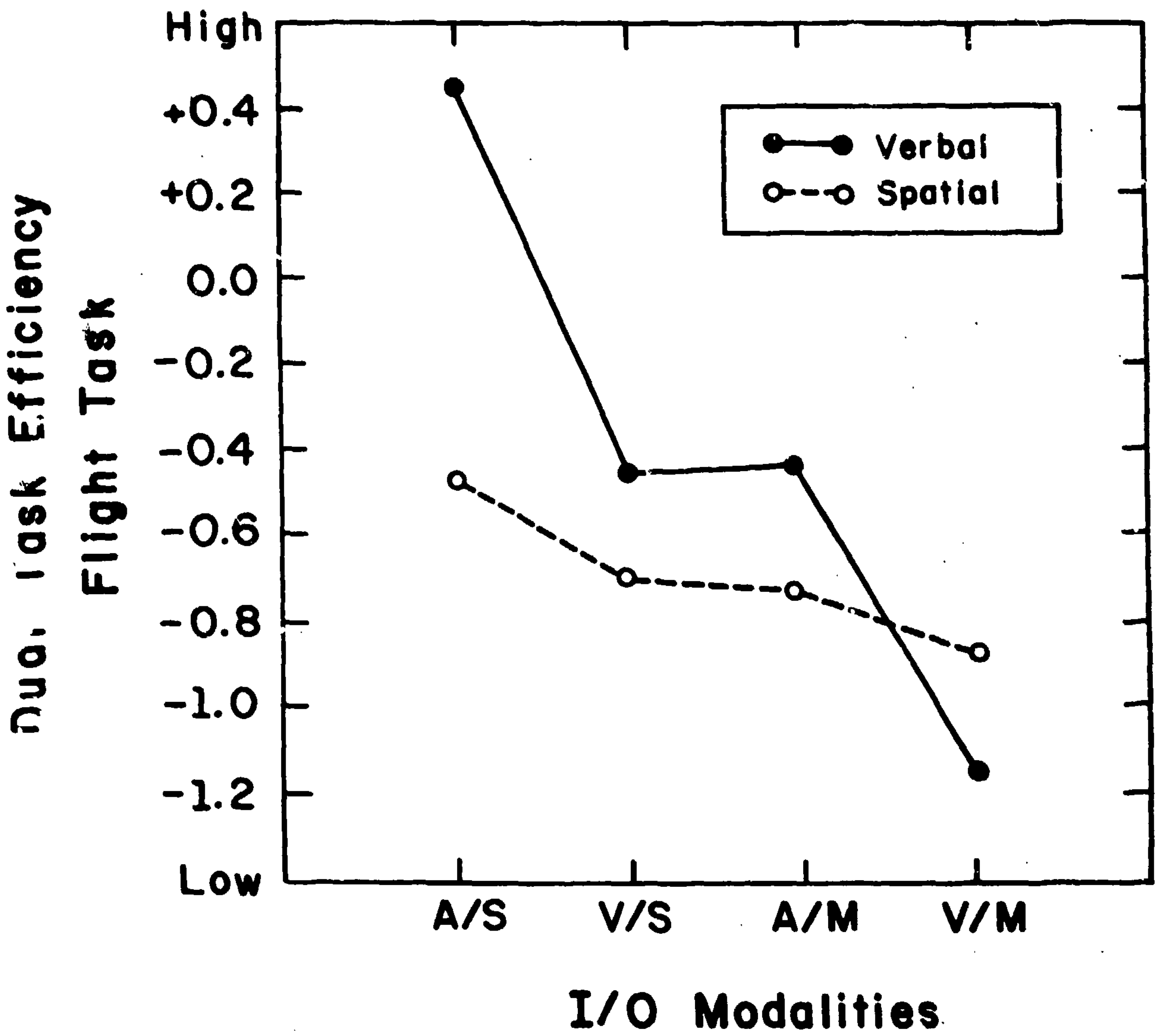


Figure 13: Dual Task Flight Task Efficiency.

Statistical analysis of the FOM decrement data was accomplished with a 6-way (task x subject x level x input x output x replication) analysis of variance. The analysis of variance showed a reliable main effect of central task interference ($F(1,7) = 5.15$, $p < .05$) which supported the prediction that the spatial task would show more interference than the verbal with the "spatial" flight task. When considered over both tasks, main effects of resource competition at both input ($F(1,7) = 28.17$, $p < .01$) and output ($F(1,7) = 5.33$, $p < .05$) were significant. Despite the apparently steeper function of the verbal task efficiency task efficiency measure with resource competition, the interactions of task x input ($F(1,7) = 1.24$, $p > .05$), and task x output ($F(1,7) = 1.07$, $p < .05$), were not statistically significant. That is, any modality compatibility advantages that may have been observed in the discrete tasks did not manifest themselves in reduced interference with the flight control task. Thus the two functions are "statistically parallel" as predicted in Figure 3.

A reliable main effect of tracking difficulty level ($F(1,7) = 27.01$, $p < .01$) was found, with the mean FOM decrement for the difficult level more than four times larger than the mean for the easy condition. The task x level x output three-way interaction was also statistically significant ($F(1,7) = 17.23$, $p < .01$). A discussion of how difficulty modulated the effects of compatibility will be deferred until later.

<u>Discrete task decrements</u>. Figure 14 presents the discrete task decrement scores (RT(dual) - RT(single)), expressed as time-sharing efficiency with good performance up. Comparison of the data in Figure 14 with the hypothetical data for efficiency scores (shown in Figure 3) indicates that the verbal task function appears identical between the two figures while the spatial task function is identical only for the speech response. The two spatial-manual points in Figure 14 indicate far greater time-sharing efficiency than was originally predicted solely from their output competition. The deviation of these points suggests that any cost of overlapping modalities is overridden by the benefit to time-sharing efficiency of C-R compatibility for the spatial task. That is, better performance is obtained when C-R compatibility is maintained with the manual response in the spatial task, despite the output competition.

Statistical analysis was performed on the RT decrements with the same analysis of variance design as used for the FOM decrement data. The main effect for task was not reliable ($F(1,7) = 0.27$, $p > .05$). While this result was not predicted, on the assumption that the spatial task would show more interference than the verbal, it will be recalled that greater spatial interference was reflected in the FOM measure.

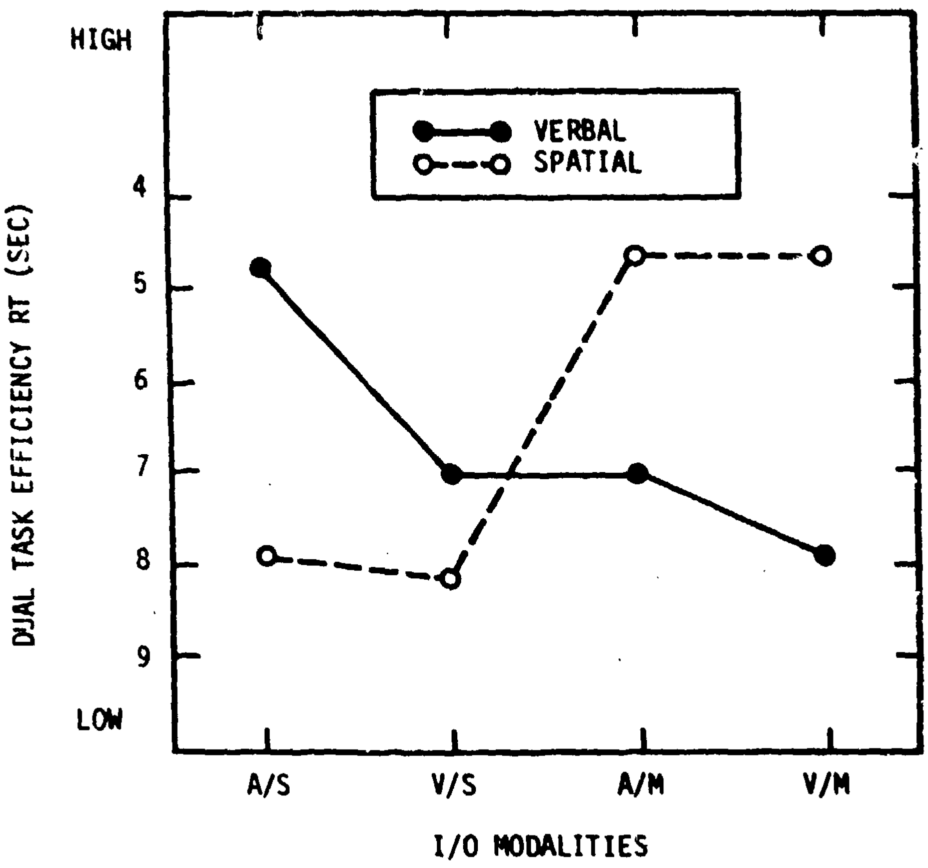


Figure 14. Discrete Task Dual Task Efficiency.

Thus, the competition for central processing resources was apparently borne by the primary flight task.

Reliable main effects for input ($F(1,7) = 46.59$), $p < .001$) and for output ($F(1,7) = 5.70$, $p < .05$) were found. As predicted, time-sharing efficiency was greater for the auditory than the visual input modality. The output, however, favored the manual response over the speech response. This seemingly counter-intuitive effect can be interpreted when both tasks are considered. In Figure 13, it is clear that a greater toll was imposed on tracking performance when the manual output was used for the side task. Furthermore, examination of Figure 14 reveals that the only source of increased efficiency in the manual condition is with the C-R compatible spatial task (see preceding section). The verbal task shows a modest decrement in the direction favored by resource competition. The finding that the continuous control task, rather than the discrete task, bore the decrement of manual response competition is consistent with results obtained by Vidulich and Wickens (1980) and will be discussed further below.

The differential effect of output competition on the spatial and verbal task is manifest in the statistically reliable task x output interaction ($F(1,7) = 39.74$, $p < .001$) with the spatial task obtaining better efficiency with the manual response than with the speech, and the verbal task showing the reverse effects. The task x input interaction was also found to be statistically significant ($F(1,7) = 41.75$, $p < .001$) as seen in Figure 14. In the verbal task, a large cost was imposed by sharing input modalities, while with the spatial task, the cost of shared input channels was minimal. Both of the modality x task interactions, unpredicted in the theoretical representations of Figure 3, suggest that the compatibility of input and output assignments for the verbal and spatial task, respectively, influence the efficiency with which time-sharing takes place.

The RT decrement scores showed a reliable main effect of tracking difficulty level ($F(1,7) = 36.12$, $p < .001$), as well as significant interactions between task x level x output ($F(1,7) = 26.84$, $p < .01$), and task x level x input x output ($F(1,7) = 13.77$, $p < .01$). A discussion of these effects will be deferred.

Dual Task Performance

As previously discussed, the measure of most importance to the system designer is the absolute level of dual task performance. Conceptually, this was represented in Figure 4 where the ordinate (moving left to right) generated increasing interference with the VM primary task and increasing S-C-R compatibility for a spatial task.

These two trends were predicted to cancel each other and make dual performance of the spatial task relatively less sensitive to input-output modalities. For the verbal task moving from left to right generated increased interference with the VM primary task and decreased S-C-R compatibility. These trends wree expected to reinforce each other and make the verbal function acutely sensitive to i/o modalities. Whether the functions are reflected in performance of one or the other or both tasks depends upon the operator's resource allocation policy since, in the present experiment, neither task was designated "primary"; therefore dual task performance of both tasks was expected to reflect some of these trends.

Dual task flight task performance. The data in Figure 15 represent the dual task performance data for the flight task. The performance measure, FOM-during, is represented on the ordinate of Figure 15. In comparing Figure 15 to the hypothetical data of Figure 4 similar patterns emerge. The spatial task function appears to be relatively less sensitive than the verbal to changes in the input-output modalities, in that the verbal function is steep while the spatial is relatively flat. The deviations of the two spatial-manual points again emphasizes the importance of C-R compatibility for the spatial task as discussed previously. The relative magnitude of the benefit of C-R compatibility is larger than that of the cost of overlapping modalities. As in Figure 14, evaluation of the four middle points indicate the dominance of C-R over S-C compatibility.

Statistical analysis was performed on the FOM-during scores with a similar analysis of variance design to that used with the decrement increase. The main effect for task was not reliable ($F(1,7) = 0.18$, $p > .05$). Reliable main effects for input ($F(1,7) = 5.96$, $p < .05$) and for output ($F(1,7) = 8.65$, $p < .05$) were found. These were in the same direction as those reported in the FOM decrement scores and indicate that the advantages of auditory input and speech output are consistent with the multiple resources/separate channels assertion since the flight task was visual-manual.

The interaction of task x output was statistically reliable ($F(1,7) = 8.77$, $p < .05$). Dual task flight performance was hindered with a vocal response to the spatial task; with the verbal task it was hindered by the manual response. The task x input interaction was found to be nonsignificant statistically ($F(1,7) = 3.10$, $p > .05$) as both the verbal and the spatial task favored auditory input. However, examination of Figure 15 suggests that the effect is in the predicted direction with the verbal task benefitting more from auditory input than the spatial (particularly with the manual response). Thus, the effect of input competition in this case is shown more on the discrete task, whose input is varied, and not on the flight task (see next section). Similar results were reported in Vidulich and Wickens (1981)

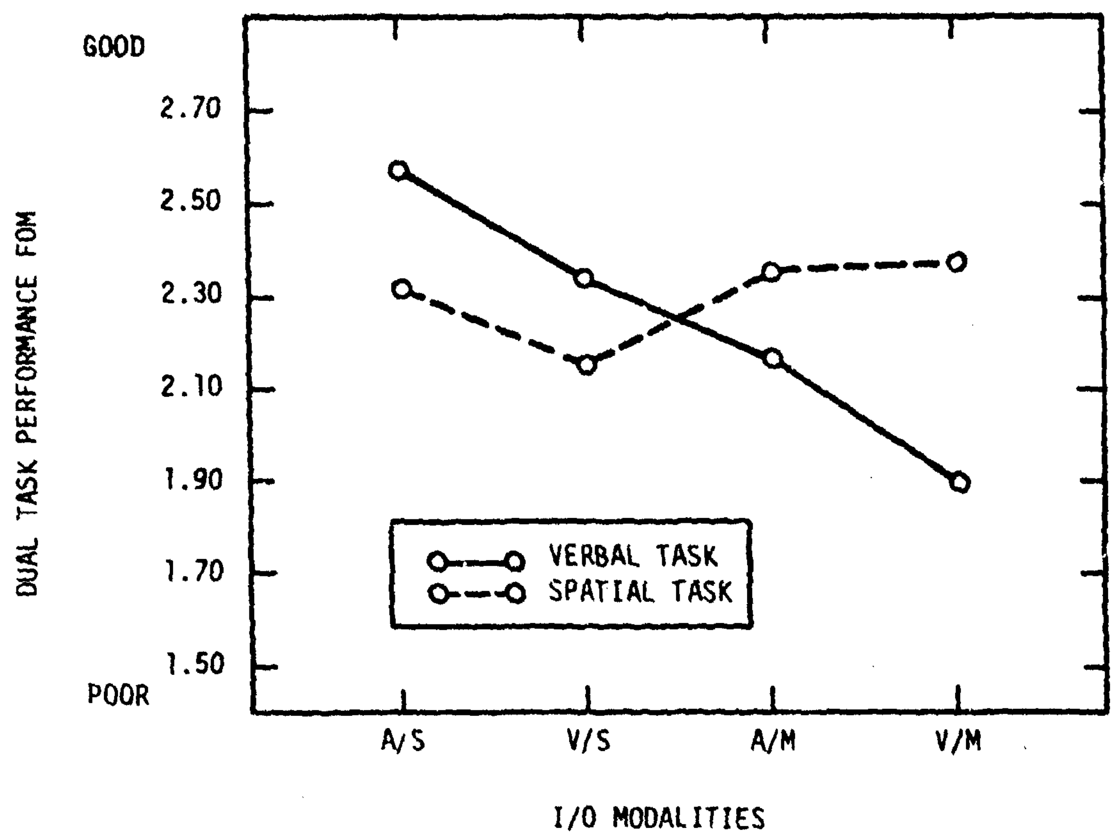


Figure 15. Flight Task Dual Task Performance.

and will be discussed in more detail in a later section. A statistically significant task x level interaction ($F(1,7) = 9.22$, $p < .05$), and a significant level x output interaction ($F(1,7) = 11.10$, $p < .05$) were found for the FOM dual task scores and will be discussed below.

Dual task discrete task performance. Figure 16 represents the dual task reaction time data, for the discrete tasks across the four different input-output modality combinations. Error rates for the reaction time tasks are shown in Figure 16 in parentheses. Since these generally correlated positively with RT, differences in RT are not apparently the result of a speed-accuracy tradeoff.

Since Figure 16 is a linear combination of Figures 12 and 14, it reflects and amplifies the similar trends in each. These are the reinforcing effects of S-C-R incompatibility and modality overlap for the verbal task, and the cancelling trends of these two factors for the spatial task. As noted above, the high dual task performance of the two spatial-manual conditions in Figure 16 again stresses the importance of C-R compatibility in the spatial case.

Statistical analysis of the dual task RT data was accomplished using the same 6-way analysis of variance. The auditory input produced reliably faster dual task responses than did the visual ($F(1,7) = 46.79$, $p < .001$). This effect is probably jointly attributable to the artifact of timing discussed previously and to input modality competition with the visual-manual tracking task. A main effect for output was also found statistically significant, favoring the manual response ($F(1,7) = 62.56$, $p < .0001$). The faster manual response was possibly an artifact of the timing mechanism, but also reflects the overwhelming advantage to the manual spatial condition.

As is indicated in the figure, the verbal task was helped by the auditory modality while the spatial task was hindered ($F(1,7) = 52.53$, $p < .001$), and the verbal task was helped by speech responses while the spatial task was hindered ($F(1,7) = 9.12$, $p < .05$). These findings were consistent with predictions.

A reliable main effect for level ($F(1,7) = 55.39$, $p < .0001$) was found for the dual RT task scores. As well as significant task x level x output ($F(1,7) = 23.74$, $p < .01$) and task x level x input x output ($F1,7) = 5.34$, $p < .05$) interactions. We shall now consider the manner in which difficulty modulated the other effects.

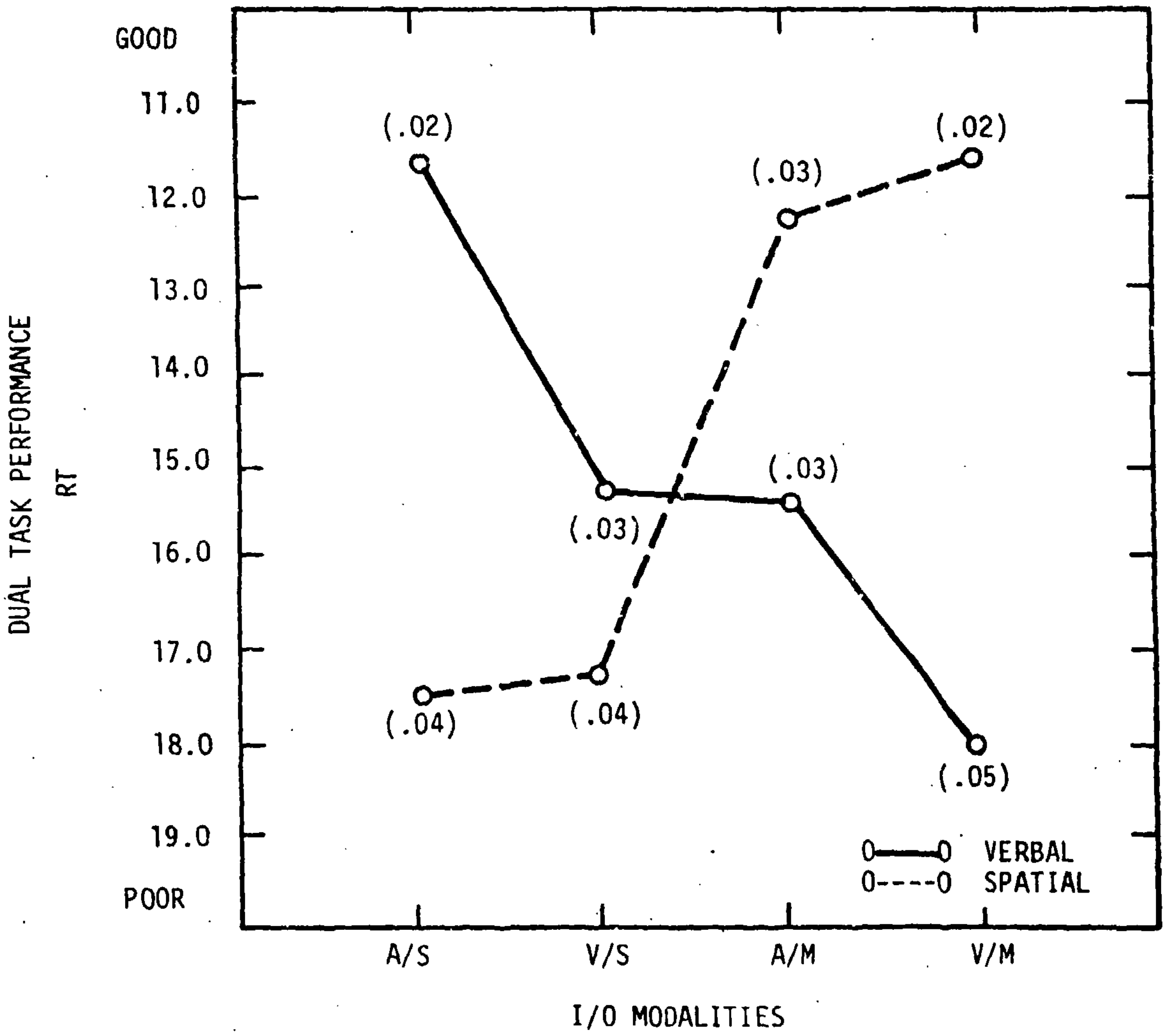


Figure 16. Discrete Task Dual Task Performance.

Effects of Flight Task Difficulty

The effects of the flight task difficulty manipulation are generally consistent across all of the four dependent variables described above. Two dependent variables, the flight task time-sharing efficiency measure and the discrete task dual task measure are shown to provide prototypical results of this manipulation in Figures 17 and 18, respectively. In these figures, the verbal task data are in the left panel, the spatial in the right. Within each panel, the difficulty effect is reflected by the slope of each graph. A downward slope reflects a performance loss with increasing difficulty. Finally, the conditions of highest and lowest compatibility for each task are indicated by heavy lines. These effects, whose statistical reliability was reported in the preceding pages, may be described as follows:

1. The main effect of difficulty was reliable in generating poorer performance in both efficiency measures and in the discrete task dual task measure. While the difficulty effect was not entirely consistent when the dual task flight measure was examined, it was reflected strongly in this measure when the verbal task was performed, particularly with the incompatible manual response.
2. The most consistent and informative effect was the task x difficulty x output interaction. Like the main effect of difficulty, this interaction was reliable for both of the time-sharing efficiency measures and the discrete task dual task interference. Figures 17 and 18 depict this interaction and reveal that for the verbal task, performance with the C-R compatible speech response is unaffected by difficulty, but performance with the incompatible manual response declines. For the spatial task this interaction is completely reversed: The now incompatible speech response is harmed, while the now compatible manual response is not.
3. The reliable four-way interaction between task difficulty output and input, reflected in both of the two discrete task measures suggests that the three-way interaction described above is different in the two modalities. However, it is most readily interpreted in terms of the following description of the data in Figure 17. For the spatial task, the over-powering dominance of C-R compatibility solely influences the effect of difficulty: Speech responses suffer with difficulty while manual responses are slightly improved. For the verbal task, on the other hand, input modality now exerts an influence particularly with the manual response. This influence is in the expected direction of the compatible auditory input suffering less from difficulty increases than the incompatible manual input.

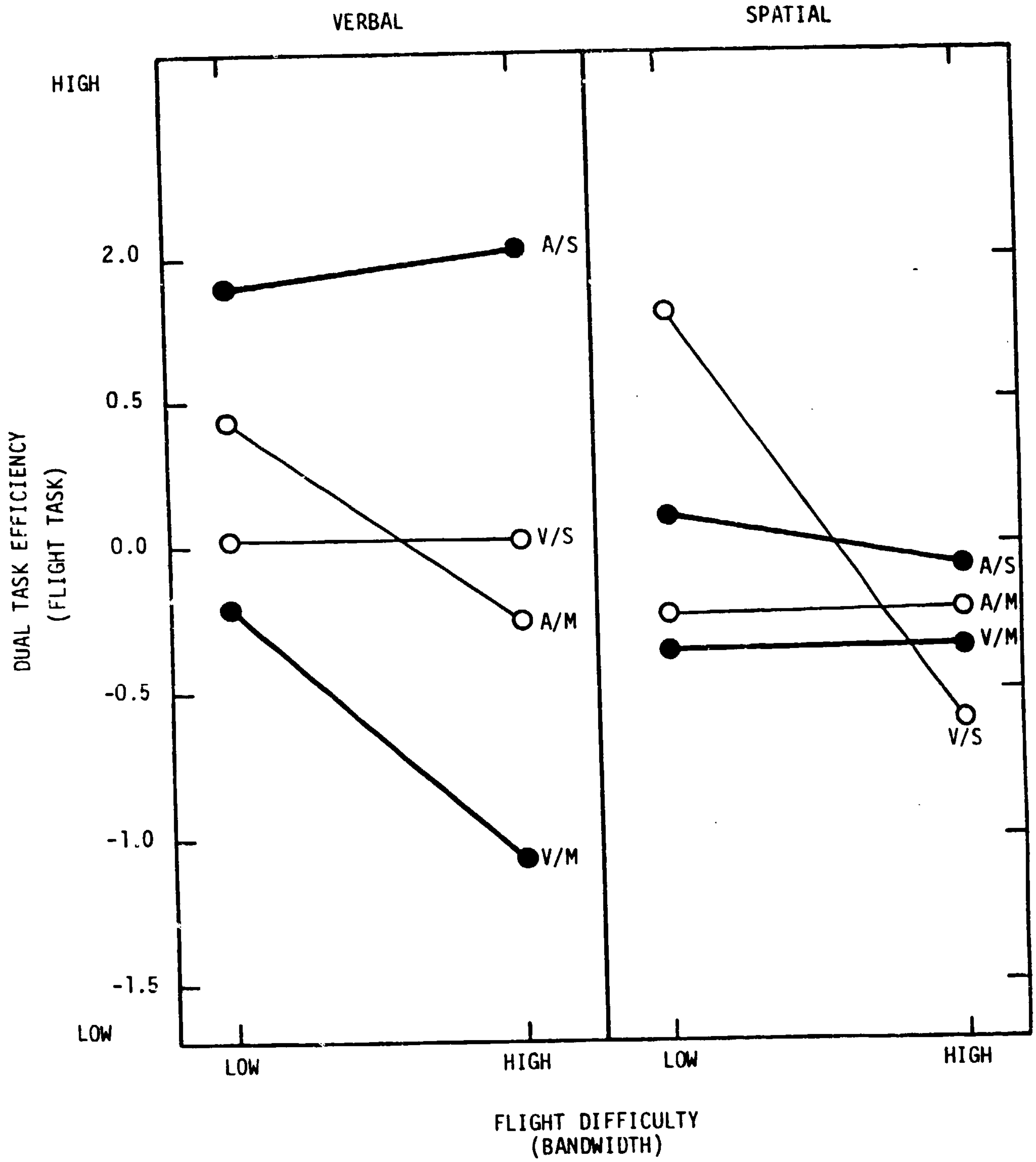


Figure 17. Flight Task Dual Task Efficiency as a Function of Difficulty.

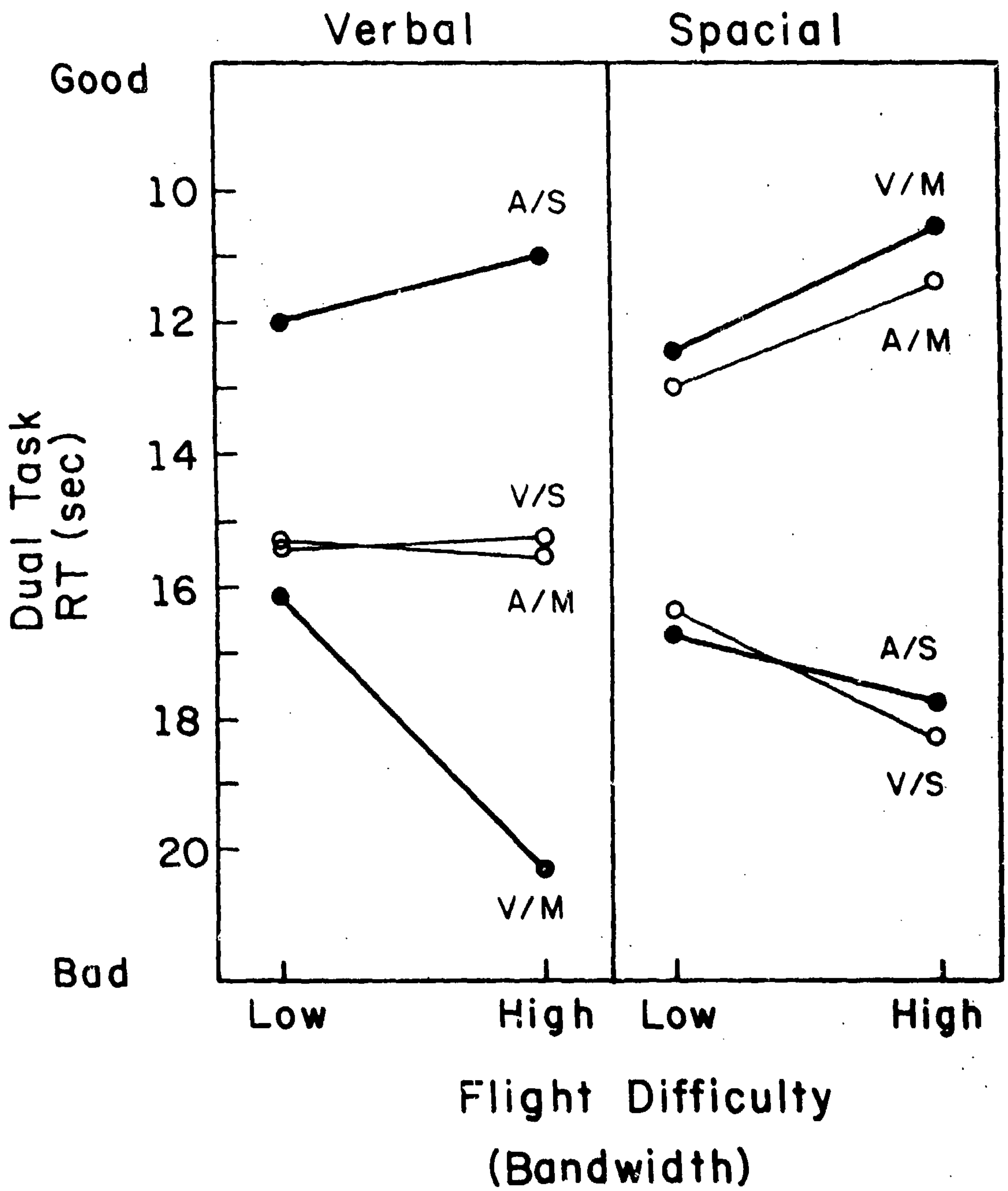


Figure 18. Dual Task Discrete Task Performance as a Function of Difficulty.

Subjective Data

Each subject was asked to rank order the difficulty of tasks within the following five subsets. (1) Primary flight task (2 levels), (2) Verbal single task (4 levels), (3) Verbal dual task collapsed over flight task difficulty (4 levels), (4) Spatial single task (4 levels), and (5) Spatial dual task collapsed over flight task difficulty (4 levels)

The influence of flight task difficulty was pronounced, despite the absence of performance differences reported above. Every subject rated the high bandwidth condition as more difficult than the low. The subjective ratings of the two tasks in single and dual task conditions were averaged, and are presented in Figures 19 and 20, respectively, in the analogous format to the performance data described above. Attention may be drawn to three general characteristics of these data: (1) Subjects agreed quite closely in their rankings. With each of the four data sets the Kendall coefficient of concordance was computed and was uniformly high [$W(6) \leq .10$, $p < .001$].

Generally speaking, the data trends agree with performance measures. Subjective difficulty of the verbal and spatial tasks appears to be affected differently by i/o modality combinations, in a direction similar to that found with performance. Note that the absolute level of the spatial and verbal functions cannot be meaningfully contrasted, since rankings were only taken within a task type.

(3) The one interesting departure of the subjective and performance data is reflected in the spatial condition of single task performance. Figure 12 indicated a clear performance advantage for the A/M over the V/S condition -- an advantage attributed to the C-R compatibility of the manual response, which was enhanced in dual task conditions. Yet Figure 19 suggests clearly that the V/S condition was preferred. In fact, eight of nine subjects rated the V/S condition as easier than the A/M, while these two assignments no longer differ from each other in perceived difficulty under dual task conditions (Figure 20). The strong performance advantage of the A/M condition over the V/S and A/S shown in Figures 14-16 is no longer present.

Discussion

The relatively complex effects of the modality, task, and difficulty manipulations can be best interpreted within the framework of the two main variables, compatibility and resource competition, investigated in this experiment. Each shall be considered in turn.

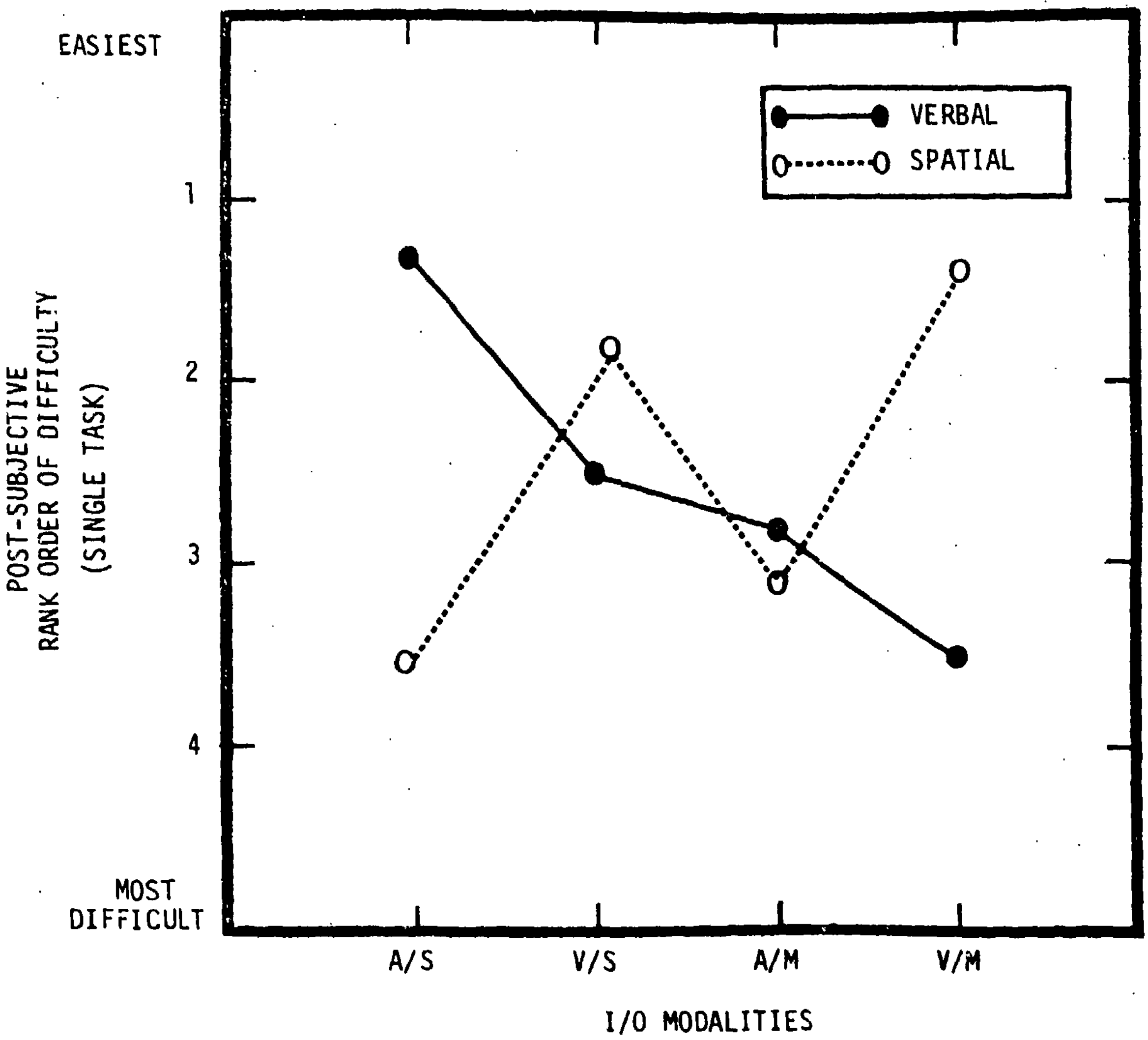


Figure 19. Single Task Discrete Task Ratings of Subjective Difficulty.

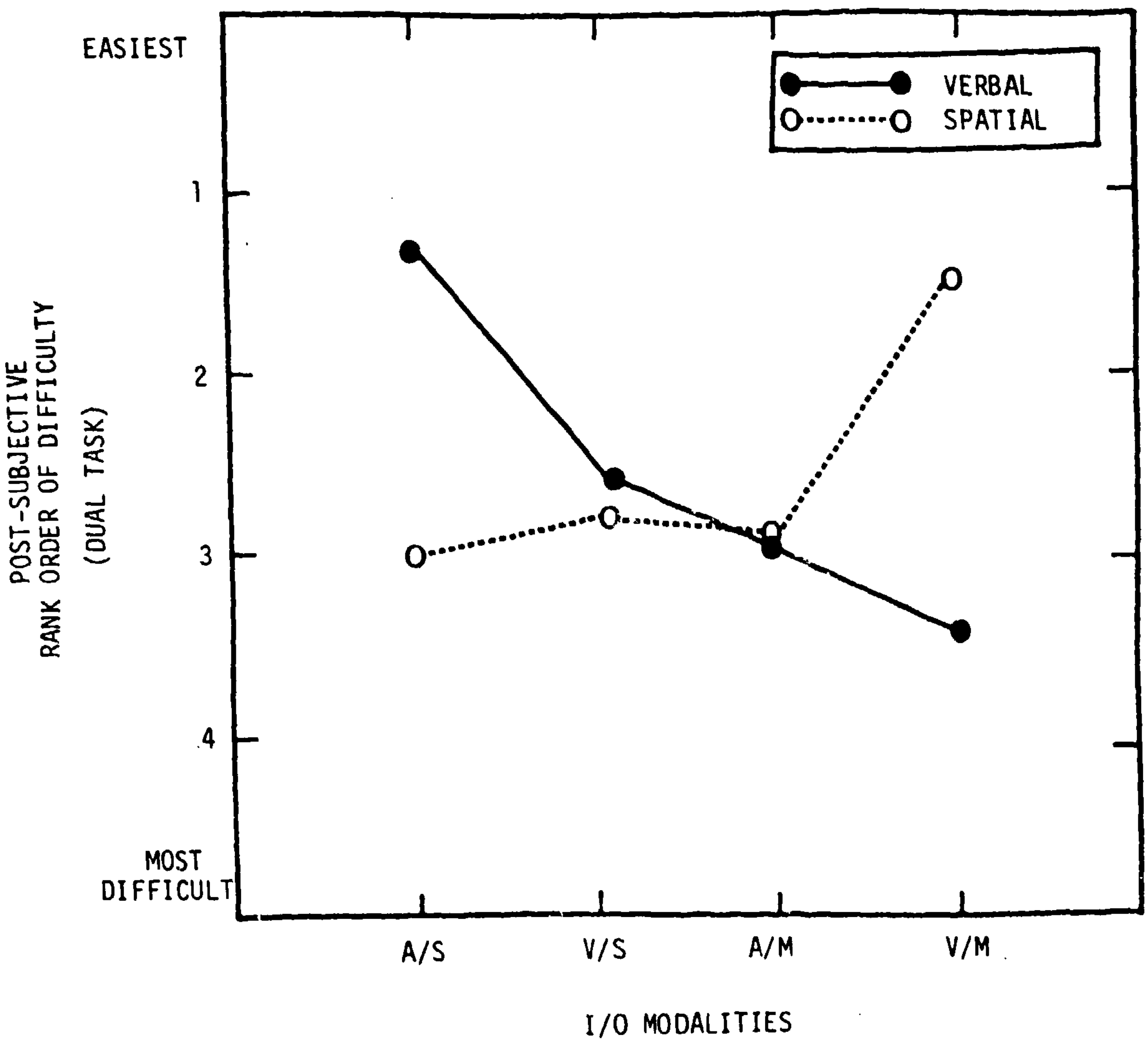


Figure 20. Dual Task Ratings of Subjective Difficulty (collapsed across flight task difficulty levels).

S-C-R Compatibility

The effect of S-C-R compatibility was dominant, as it was exerted in the predicted direction in single task performance (Figure 12), and was amplified under time-sharing conditions (Figure 16). Compatibility also influenced the magnitude of the discrete task decrement (Figure 14) in a manner similar to that observed by Ogden, Anderson, and Rieck (1979). Furthermore, the compatibility effects appeared to modulate the influence of task difficulty. Performance with compatible relations for each task was unaffected by increases in flight task demand, while performance with incompatible relations was harmed (Figures 17 & 18).

The specific compatibility effect may be partialled into S-C and C-R effects for each task separately. When this is done, the most pronounced effect was with C-R compatibility effect found for the spatial task. It is unclear to what extent this effect may be an artifact of physical constraints in the speech control condition, rather than a reflection of human information processing limitations. As noted in the Methods Section, the same maximum velocity of cursor slewing was available in both control modes. Furthermore, the use of 12 direction indicators provided a reasonable degree of analog control for the speech task. Thus, as long as a single movement is required, there is little mechanical difference between performance of the two systems. However, it is probable that some limitations in this task were incurred when it was necessary to apply a mid-course correction with speech control, and this may have contributed somewhat to the added delay. It is probable, however, that a major component was simply the less natural compatibility of verbal control of spatial movement.

In contrast, the verbal task was hampered by the manual response. In dual task conditions, this disruption may have been partially attributable to the involvement with the visual system in guiding the manual keypress response. However, this scanning factor cannot account for the manual inferiority under single task conditions in which there was no competition for the visual channel. This would be particularly true in the auditory input condition; yet the speech advantage is still present (compare the verbal A/S and A/M points in Figure 12). Thus, the C-R compatibility effect manifest here seems to be a direct reflection of Greenwald's principle of ideomotor compatibility. Verbal working memory is best off-loaded with a speech response.

The effects of S-C compatibility were generally less pronounced than those of C-R compatibility. This difference is reflected in performance in the four conditions in which S-C and C-R compatibility are pitted against each other--i.e., the four middle points of Figures 12-15. Here, in all cases but Figure 13 (dual task flight efficiency), maintenance of C-R and violation of S-C compatibility "wins" over the converse relation, that is, the four points form an "x." Still S-C compatibility was observed as reflected by the interaction of task by input modality shown in both single task performance (Figure 12) and in dual task efficiency (Figures 13 & 14). For the verbal task, this effect appears to be a direct extension of the auditory advantage found in short term memory recall investigated by Murdock (1968); Watkins (1972), and Nilson (1976).

The effect of S-C compatibility for the spatial task was weaker still. In dual task conditions, the advantages of the visual input was more than dominated by the cost of competition for visual resources with the primary flight task. Nevertheless, in single task conditions the S-C compatibility advantage is still present (see Figure 12). In retrospect, it is somewhat surprising that a S-C compatibility was found at all with the spatial task. This is because, while the visual channel is S-C compatible for the spatial task, the configuration used a visual-verbal format (i.e., print), rather than a visual-spatial one (an arrow designating the target). The issue of differential compatibility between the four formats of input (visual-auditory, verbal, spatial) was not addressed in the present design. Presumably, however, a visual-spatial display would have enhanced spatial performance still further, as it is more compatible with spatial localization than a visual-verbal (printed) identification of the target.

Resource Competition

By in large, the results were quite consistent with predictions made from the multiple resource model as depicted in Figure 1. The effect of increased central processing competition for spatial resources was manifest in the decreased time-sharing efficiency of the spatial, as opposed to the verbal discrete task when each was shared with the primary flight task (Figure 13). This effect replicates that observed under more controlled laboratory conditions by Wickens, Sandry, and Micalizzi (1981), and by Baddeley and Leiberman (1980). As suggested by comparing Figures 13 and 14, the effect of central processing resource competition was borne more by the tracking than by the discrete task. It is possible, of course, that the difference in competition could be attributed to the greater overall difficulty of the spatial task. This appears to be somewhat unlikely since both tasks were performed equivalently under single task conditions. However, since the relative comparisons of difficulty of the two was not assessed via subjective measures, this possibility cannot be ruled out altogether.

The effect of competition for input and output modalities was generally consistent with the effects predicted in Figure 3, as shown in Figure 13: A monotonic decrease in time-sharing efficiency with increasing i/o overlap. This is a trend that agrees with the results of similar manipulations by Wickens (1980) and Vidulich and Wickens (1981). It should be noted, however, that the monotonic trend is consistently revealed only in the flight task interference measure. When the discrete task interference is considered (Figure 14), the spatial task reveals an asymmetry of resource allocation, which was manifest also in the investigations by Vidulich and Wickens (1981) and by Wickens (1980). When a common manual output modality is shared between tasks, the continuous control task shares the brunt of the response resource competition, while the discrete task is barely effected at all--in fact, is effected less than when a speech response is employed. This result seems to suggest a pre-emptive dominance of the discrete task over the continuous one when the two share demand for the common manual resource. The fact that this dominance was manifest in the three independent investigations suggests that it is a consistent, reliable phenomenon.

Resource Competition and Compatibility in Combination

Both models of resource competition and S-C-R compatibility were able to successfully predict performance. The effects of the two variables in combination were not quite additive. This is suggested by the data in Figures 15 and 16, indicating that compatibility enhances time-sharing efficiency; or alternatively that compatibility effects are enhanced under dual task conditions. Were complete independence or additivity obtained, then the spatial and verbal functions should be parallel, as in Figure 3. In Figure 13 they appear to converge (although the interaction was not quite statistically reliable), and in Figure 14, they reliably interact both with regard to input and to output modality. This interaction between the two factors prevents one from predicting with precision the absolute level of dual task performance from the individual components. However, the fact that dual task loading enhances compatibility effects allows the safe conclusion to be drawn that varying i/o modalities of a task performed concurrently with flight control, will have a more pronounced effect if the task is verbal than if it is spatial. Only the precise magnitude of the relative contributions of compatibility and resource competition must be evaluated by a careful consideration of the tasks at hand. In summary, the results suggest that verbal tasks will be those that are best served by voice recognition and synthesis technology.

Subjective measures. The subjective measures of task difficulty generally substantiate the performance trends that were found. While these measures were not collected in a carefully controlled setting, they do appear to be both systematic and reliable. The particular point of disagreement between subject perception and performance, however, is worthy of note. Subjects found it easier, subjectively to perform the spatial task with the A/S than with the V/M assignment; yet they performed more poorly under the more preferred A/S condition. In dual task conditions they preferred the two assignments equally, but again performed more poorly and suffered far greater interference with the V/M condition. These data provide yet another example of potential dissociations between subjective and performance data in workload assessment. Wickens (1981) and Wickens and Derrick (1981) have discussed this issue at some length. While the reason for the dissociation in the present data is not immediately apparent, it nevertheless serves as a reminder to the system designers that information provided by the two classes of measures may not always be equivalent. To the extent that they are not, serious consideration must be given as to which should guide the formulation of design decisions.

Acknowledgments

The authors wish to gratefully acknowledge the cooperation of two individuals who made invaluable contributions to the success of this project: Dr. Sam Schiflett who made available the facilities of the Naval Air Test Center, and who participated in many aspects of the conceptualization and data collection phase of this study, and Mr. Joe Alfano who performed the computer programming necessary to implement the tasks.

References

Allport, D.A., Antonis, B., & Reynolds, P. On the division of attention: A disproof of the single channel hypothesis. Quarterly Journal of Experimental Psychology, 1972, 24, 225-235.

Alwitt, L.F. Two neural mechanisms related to modes of selective attention. Journal of Experimental Psychology: Human Perception and Performance, 1982, 7, 324-332.

Anderson, J.R. Cognitive psychology and its implications. San Francisco: W.H. Freeman, Inc., 1980.

Baddeley, A.D. & Hitch, G.J. Working memory. In G. Bower (Ed.), Recent Advances in Learning and Motivation VIII. New York: Academic Press, 1974.

Baddeley, A.D. & Lieberman, K. Spatial working memory and imagery nmeumonics. In R. Nickerson (Ed.), Attention and Performance VIII. Englewood Cliffs, NJ: Erlbaum, 1980.

Bradshaw, J.L. & Perriment, A.D. Laterality effects and choice reaction time in a unimanual two-finger task. Perception and Psychophysics, 1970, 7, 185-189.

Brainard, R.W., Irby, T. S., Fitts, P.M., & Alluisi, E. A. Some variables influencing the rate of gain of information. Journal of Experimental Psychology, 1962, 63, 105-110.

Broadbent, D.E. & Gregory, M. On the interaction of S-R compatibility with other variables affecting reaction time. British Journal of Psychology, 1965, 56, 61-67.

Bryden, M.P. Tachistoscopic recognition, handedness, and cerebral dominance. Neuropsychologia, 1965, 3, 1-8.

Bryden, M.P. Measuring handedness with questionnaires. Neuropsychologia, 1977, 15, 617-624.

Crovitz, H.E. & Zener, K. A group-test for assessing hand and eye dominance. American Journal of Psychology, 1962, 75, 271-276.

Dimond, S.J. & Beaumont, J.G. Processing in perceptual integration between and within the cerebral hemispheres. British Journal of Psychology, 1972, 63, 509-514.

Edman, T.R. Human Factors Guidelines for the Use of Word Recognition Devices, 25th Annual Meeting of the Human Factors Society, Rochester, NY, 1981.

Fitts, P.M. & Deininger, R.L. S-R compatibility: Correspondence among paired elements within stimulus and response codes. Journal of Experimental Psychology, 1954, 58, 483-492.

Fitts, P.M. & Seeger, C.M. S-R compatibility: Spatial characteristics of stimulus and response codes. Journal of Experimen'al Psychology, 1953, 46, 199-210.

Fozard, J.L., Carr, G.D., Talland, G.A., & Erwin, D. E. Effect of information load, sensory modality, and age on paced inspection performance. Quarterly Journal of Experimental Psychology, 1971, 23, 304-310.

Geffen, G., Bradshaw, J.L., & Wallace, G. Interhemispheric effects on reaction time to verbal and nonverbal visual stimuli. Journal of Experimental Psychology, 1971, 87, 415-422.

Green, J. & Well, A.D. Interference between processing demands within a cerebral hemisphere. Paper presented at Psychonomics Society Meeting, Washington, D.C., November, 1977.

Greenwald, A.G. Sensory feedback mechanisms in performance control with special reference to the ideo-motor mechanism. Psychological Review, 1970, 77, 73-79.

Greenwald, A.G. Time-sharing, ideomotor compatibility, and automaticity. Proceedings, 23rd Annual Meeting of the Human Factors Society, Boston, 1979.

Greenwald, A.G. & Shulman, H.G. On doing two things at once. Eliminating the psychological refractory period effect. Journal of Experimental Psychology, 1973, 101, 70-76.

Gross, M. Hemispheric specialization for processing of visually presented verbal and spatial stimuli. Perception and Psychophysics, 1972, 12(4), 357-363.

Hammond, K.R. The integration of research in judgment and decision theory. University of Colorado Institute for Behavioral Science Report #226, July, 1980.

Isreal, J. Structural interference in dual-task performance: Event-related potential, behavioral, and subjective effects. Unpublished doctoral dissertation, University of Illinois, 1980.

Kantowitz, B.H. & Knight, J.L., Jr. Testing tapping time-sharing, II: Auditory secondary task. Acta Psychologia, 1976, 40, 343-362.

Kimura, D. Dual functional asymmetry of the brain in visual perception. Neuropsychologia, 1966, 4, 275-285.

Kimura, D. Spatial localization in left and right visual fields. Canadian Journal of Psychology, 1969, 23, 445-453.

Kinsbourne, M. & Hicks, R. Functional cerebral space. In J. Requin (Ed.), Attention and Performance VII, Hillsdale, NJ: Erlbaum, 1978.

Klatzky, R.L. & Atkinson, R.C. Specialization of cerebral hemispheres in scanning for information in short-term memory. Perception & Psychophysics, 1971, 10, 335-338.

Lea, W. Trends in Speech Recognition. Englewood Cliffs, NJ: Prentice Hall, 1978.

McLeod, P. A dual task response modality effect: Support for multiprocessor models of attention. Quarterly Journal of Experimental Psychology, 1977, 29, 651-667.

Moscovitch, M. Information processing and the cerebral hemispheres. In M.S. Gazzaniga (Ed.). The Handbook of Behavioral Biology: Volume on Neuropsychology. New York: Plenum Press, 1979.

Moscovitch, M. & Klein, D. Material specific perceptual interference for visual words and faces: Implications for models of capacity limitations, attention, and laterality. Journal of Experimental Psychology: Human Perception and Performance, 1980, 6, 590-604.

Murdock, B.B. Modality effects in short term memory: Storage or retrieval? Journal of Experimental Psychology, 1968, 77, 79-86.

Navon, D. & Gopher, D. On the economy of the human processing system. Psychological Review, 1979, 86, 214-255.

Nilsson, L.G., Ohlsson, K., & Ronnberg, J. Capacity differences in processing and storage of auditory and visual input. In S. Dornick (Ed.), Attention and Performance VI, Hillsdale, NJ: Erlbaum, 1977.

Ogden, G.D., Anderson, N.S., & Rieck, A.M. Dual task measures of S-R compatibility. 23rd Annual Meeting of the Human Factors Society, Boston, Mass., 1979.

Pachella, R.G. The interpretation of reaction time in information processing research. In B. Kantowitz (Ed.), Human Information Processing: Tutorials in Performance and Cognition. Hillsdale, NJ: Lawrence Erlbaum Associates, 1974.

Rizzolatti, G., Umilta, C., & Berlucchi, G. Opposite superiorities of the right and left cerebral hemispheres in discriminative reaction time to physiognomical and alphabetical material. Brain, 1971, 94, 431-442.

Rollins, H. & Hendricks, R. Processing of words presented simultaneously to eye and ear. Journal of Experimental Psychology: Human Perception and Performance, 1980, 6(1), 99-109.

Schell, B. & Satz, P. "Nonverbal" visual half-field perceptions and hemispheric asymmetry. Proceedings, 78th Annual Convention of the American Psychological Association, Miami, 1970.

Shaffer, L.H. Multiple attention in continuous tasks. In P.M. Rabbitt & S. Dornic (Eds.). Attention and Performance V, London: Academic Press, 1975.

Simon, J.R., Hinrichs, I.V., & Craft, J.L. Auditory S-R compatibility: Reaction time as a function of ear-hand correspondence and ear-location correspondence. Journal of Experimental Psychology, 1970, 86, 97-102.

Sternberg, S. The discovery of processing stages: An extension of Donder's method. Acta Psychologica, 1969, 30, 276-315.

Teichner, W.H. & Krebs, M.J. Laws of visual choice reaction time. Psychological Review, 1974, 81(1) 75-98.

Teitelbau, H., Sharpless, S.K., & Byck, R. Role of somatosensory cortex in interhemispheric transfer of tactile habits. Journal of Comparative & Physiological Psychology, 1968, 66, 623-632.

Treisman, A. & Davis, A. Divided attention between eye and ear. In Kornblum, S. (Ed.), Attention and Performance IV. New York: Academic Press, 1973.

Umilta, C. Factors affecting face recognition in the cerebral hemispheres familiarity and naming. In J. Requin (Ed.), Attention and Performance VII, New Jersey: Erlbaum, 1978.

Vidulich, M. & Wickens, C.D. Time-sharing manual control and memory search: The joint effect of input and output modality competition, priorities, and control order, University of Illinois Engineering-Psychology Lab. Technical Report EPL-81-4/ONR-81-4, December, 1981.

Vinje, E.W. Flight simulator evaluation of audio displays for IFR hover control. Proceedings of the Eight Annual Conference on Manual Control, 1972.

Wallace, R.J. S-R compatibility and the idea of a response code. Journal of Experimental Psychology, 1971, 88, 354-360.

Watkins, M.J. Locus of the modality effect in free recall. Journal of Verbal Learning and Verbal Behavior, 1972, 11, 644-648.

Wickelgren, W. Cognitive Psychology. New Jersey: Prentice-Hall, 1979.

Wickens, C.D. The structure of attentional resources. In R. Nickerson (Ed.). Attention and Performance VIII, Englewood Cliffs, NJ: Lawrence Erlbaum, 1980.

Wickens, C.D. Processing resources in attention, dual task performance, and workload assessment. University of Illinois Engineering Psychology Lab. Technical Report EPL-81-3/ONR-81-3, July, 1981.

Wickens, C.D., Mountford, S.J., & Schreiner, W.S. Time-sharing efficiency: Evidence for multiple resources, task-hemispheric integrity, and against a general ability. Human Factors, 1981, 22, 211-229.

Wickens, C.D. & Sandry, D.L. An investigation of the dual task performance relationship to hemispheric specialization. University of Illinois Engineering Psychology Lab Technical Report EPL-80-1/ONR-80-1, June, 1980.

APPENDIX A

Assessment of Handedness (Bryden, 1977)

NAME: ____

Have you ever had any tendency to left handedness?

YES NO

Please indicate your preferences in the use of hands in the following activities by putting "+" in the appropriate column. Where the preference is so strong that you would never try to use the other hand unless absolutely forced to, put "++". If in any case you are really indifferent, put "+" in both columns.

Please try to answer all the questions, and only leave a blank if you have no experience at all of the object or task.

		R	L
1	Writing		
2	Drawing		
3	Throwing		
4	Scissors		
5	Comb		
6	Toothbrush		

APPENDIX A (cont.)

1. Do you consider yourself right-handed, left-handed, or ambidexterous?

____

2. Is there anyone in your family (blood relations) who is left-handed or ambidexterous? If so, who?

____

3. Were you ever considered left-handed and then for some reason changed? If so, why and when?

____

4. Is there any activity or set of activities not on this list for which you consistently use your non-dominant hand?

____

APPENDIX B

Assessment of Handedness (Crovitz and Zener, 1962)

NAME: ____________________

Answer the following questions carefully. Imagine yourself performing the activity described before answering each question. Answer by drawing a circle around the appropriate set of letters appearing to the left of each question whose meanings is:

Ra = right hand always.	Lm = left hand most of the time.
Rm = right hand most of the time.	La = left hand always.
E = both hands equally often.	X = do not know which hand.

---

(1) Ra Rm E Lm X: is used to write with.

(2) Ra Rm E Lm X: to hold nail when hammering.

(3) Ra Rm E Lm X: to throw a ball.

(4) Ra Rm E Lm X: to hold bottle when removing top.

(5) Ra Rm E Lm X: is used to draw with.

(6) Ra Rm E Lm X: to hold potato when peeling.

(7) Ra Rm E Lm X: to hold pitcher when pouring out of it.

(8) Ra Rm E Lm X: to hold scissors when cutting.

(9) Ra Rm E Lm X: to hold knife when cutting food.

(10) Ra Rm E Lm X: to hold needle when threading.

(11) Ra Rm E Lm X: to hold drinking glass when drinking.

(12) Ra Rm E Lm X: to hold tooth brush when brushing teeth.

(13) Ra Rm E Lm X: to hold dish when wiping.

(14) Ra Rm E Lm X: holds tennis racket when playing.

(Every item is scored on a 5-point scale. On items 1, 3, 5, 7, 8, 9, 11, 12, and 14, Ra is scored "1"; Rm "2"; E, "3"; Lm, "4"; and La, "5". All other items (2, 4, 6, 10, 13) are scored in the reverse fashion. Items marked X are prorated. The highest possible right-handed score is 14, and the highest left-handed score is 70.)

APPENDIX C

Commands for Verbal Concurrent Task

24 Scenarios

Scenario #1:	(a)	squawk 4371
	(b)	enter latitude north 01 18
	(c)	turn on data-link, radar-beacon, tacan
Scenario #2:	(a)	enter elevation 14300
	(b)	enter latitude south 23 29
	(c)	turn on tacan, ILS, IFF
Scenario #3:	(a)	squawk 1030
	(b)	turn on radar-beacon, IFF, ILS
	(c)	enter longitude east 36 14
Scenario #4:	(a)	enter longitude west 36 20
	(b)	turn on ILS, radar-beacon, tacan
	(c)	enter elevation 14260
Scenario #5:	(a)	squawk 1165
	(b)	enter longitude east 06 17
	(c)	turn on radar-beacon, ILS, IFF
Scenario #6:	(a)	turn on ILS, data-link, tacan
	(b)	enter elevation 11400
	(c)	enter latitude north 15 45
Scenario #7:	(a)	squawk 1312
	(b)	enter longitude east 32 53
	(c)	turn on IFF, tacan, ILS
Scenario #8:	(a)	enter longitude west 20 23
	(b)	turn on radar-beacon, data-link, ILS
	(c)	squawk 4524
Scenario #9:	(a)	squawk 4763
	(b)	enter latitude north 29 32
	(c)	turn on tacan, radar-beacon, IFF
Scenario #10:	(a)	enter longitude east 42 18
	(b)	turn on radar-beacon, data-link, ILS
	(c)	enter elevation 16720

APPENDIX C (cont.)

Scenario #11:	(a)	turn on ILS, IFF, tacan
	(b)	squawk 2134
	(c)	enter latitude south 23 58
Scenario #12:	(a)	enter longitude west 12 19
	(b)	set tacan at 106
	(c)	turn on data-link, radar-beacon, ILS
Scenario #13:	(a)	squawk 1542
	(b)	enter latitude north 36 10
	(c)	turn on IFF, ILS, data-link
Scenario #14:	(a)	enter longitude west 42 13
	(b)	enter elevation 19100
	(c)	turn on ILS, radar-beacon, tacan
Scenario #15:	(a)	enter longitude east 17 13
	(b)	squawk 1426
	(c)	turn on radar-beacon, IFF, tacan
Scenario #16:	(a)	set tacan at 119
	(b)	enter latitude south 11 14
	(c)	turn on IFF, radar-beacon, tacan
Scenario #17:	(a)	squawk 3213
	(b)	turn on data-link, radar-beacon, ILS
	(c)	enter latitude north 21 53
Scenario #18:	(a)	turn on ILS, IFF, tacan
	(b)	enter elevation 12500
	(c)	squawk 7261
Scenario #19:	(a)	set tacan at 30
	(b)	enter longitude west 34 49
	(c)	turn on IFF, radar-beacon, ILS
Scenario #20:	(a)	enter longitude east 42 49
	(b)	turn on data-link, radar-beacon, ILS
	(c)	squawk 6031
Scenario #21:	(a)	set ILS at 10
	(b)	turn on IFF, radar-beacon, ILS
	(c)	enter latitude south 12 43
Scenario #22:	(a)	squawk 2173
	(b)	turn on radar-beacon, IFF, data-link
	(c)	enter longitude east 57 36

APPENDIX C (cont.)

Scenario #23:
(a) turn on ILS, IFF, tacan
(b) squawk 0421
(c) enter latitude north 41 33

Scenario #24:
(a) squawk 1006
(b) turn on radar-beacon, tacan, IFF
(c) enter latitude south 10 46

455:MAT:716:maf
81u455-163

OFFICE OF NAVAL RESEARCH

Code 455

TECHNICAL REPORTS DISTRIBUTION LIST

CDR Paul R. Chatelier
Office of the Deputy Under Secretary
of Defense
OUSDRE (E&LS)
Pentagon, Room 3D129
Washington, D.C. 20301

Director
Engineering Psychology Programs
Code 455
Office of Naval Research
800 North Quincy Street
Arlington, VA 22217 (5 cys)

Director
Aviation & Aerospace Technology
Code 210
Office of Naval Research
800 North Quincy Street
Arlington, VA 22217

CDR P. M. Curran
Office of Naval Research
Code 270
800 N. Quincy Street
Arlington, VA 22217

Director
Physiology Program
Code 441
Office of Naval Research
800 North Quincy Street
Arlington, VA 22217

Commanding Officer
ONR Eastern/Central Regional Office
ATTN: Dr. J. Lester
Building 114, Section D
666 Summer Street
Boston, MA 02210

Commanding Officer
ONR Branch Office
ATTN: Dr. C. Davis
536 South Clark Street
Chicago, IL 60605

Commanding Officer
ONR Western Regional Office
ATTN: Dr. E. Gloye
1030 East Green Street
Pasadena, CA 91106

Director
Naval Research Laboratory
Technical Information Division
Code 2627
Washington, D.C. 20375 (6 cys)

Dr. Robert G. Smith
Office of the Chief of Naval
Operations, OP987H
Personnel Logistics Plans
Washington, D.C. 20350

Dr. W. Mehuron
Office of the Chief of Naval
Operations, OP 987
Washington, D.C. 20350

Dr. Andreas B. Rechnitzer
Office of the Chief of Naval
Operations, OP 952F
Naval Oceanography Division
Washington, D.C. 20350

Dr. Jerry C. Lamb
Naval Underwater Systems Center
Code 35
Newport, RI 02840

CDR Robert Biersner
Naval Medical R&D Command
Code 44
Naval Medical Center
Bethesda, MD 20014

Dr. Arthur Bachrach
Behavioral Sciences Department
Naval Medical Research Institute
Bethesda, MD 20014

CDR Thomas Berghage
Naval Health Research Center
San Diego, CA 92152

455:ECG:716:maf
81u455-163

Dr. George Moeller
Human Factors Engineering Branch
Submarine Medical Research Lab
Naval Submarine Base
Groton, CT 06340

Head
Aerospace Psychology Department
Code L5
Naval Aerospace Medical Research Lab
Pensacola, FL 32508

Dr. James McGrath, Code 302
Navy Personnel Research and
Development Center
San Diego, CA 92152

Dr. Henry Halff
Navy Personnel Research and
Development Center
Code 304
San Diego, CA 92152

Mr. Ronald A. Erickson
Human Factors Branch
Code 3194
Naval Weapons Center
China Lake, CA 93555

Human Factors Engineering Branch
Code 1226
Pacific Missile Test Center
Point Mugu, CA 93042

Dr. Gary Poock
Operations Research Department
Naval Postgraduate School
Monterey, CA 93940

Mr. Warren Lewis
Human Engineering Branch
Code 8231
Naval Ocean Systems Center
San Diego, CA 92152

Dr. A. L. Slafkosky
Scientific Advisor
Commandant of the Marine Corps
Code RD-1
Washington, D.C. 20380

Mr. Arnold Rubinstein
Naval Material Command
NAVMAT 0722 - Rm. 508
800 North Quincy Street
Arlington, VA 22217

Commander
Naval Air Systems Command
Human Factors Programs
NAVAIR 340F
Washington, D.C. 20361

Commander
Naval Air Systems Command
Aircrew Systems Branch
NAVAIR 5313
Washington, D.C. 20361

Mr. Phillip Andrews
Naval Sea Systems Command
NAVSEA 0341
Washington, D.C. 20362

Dr. Sam Schiflett
Human Factors Section
Systems Engineering Test
Directorate
U.S. Naval Air Test Center
Patuxent River, MD 20670

LCDR W. Moroney
Code 55MP
Naval Postgraduate School
Monterey, CA 93940

Director, Organizations and
Systems Research Laboratory
U.S. Army Research Institute
5001 Eisenhower Avenue
Alexandria, VA 22333

Judith Lind
Human Factors Branch, Code 3152
Naval Weapons Center
China Lake, CA 93555

Technical Director
U.S. Army Human Engineering Labs
Aberdeen Proving Ground, MD 21005

455:ECG:716:maf
81u455-163

U.S. Air Force Office of Scientific Research
Life Sciences Directorate, NL
Bolling Air Force Base
Washington, D.C. 20332

CDR Norman Lane
Human Factors Engineering Division
Naval Air Development Center
Warminster, PA 18974

Dr. Bryce O. Hartman
Chief, Crew Technology Division/VN
USAF School of Aerospace Medicine (AFSC)
Brooks AFB, TX 78235

LTCOL R. D. O'Donnell
6577 AMRL/HEB
Wright Patterson AFB, OH 45433

Dr. Kenneth Gardner
Applied Psychology Unit
Admiralty Marine Technology Establishment
Teddington, Middlesex TW11 OLN
ENGLAND

Director, Human Factors Wing
Defence & Civil Institute of Environmental Medicine
Post Office Box 2000
Downsview, Ontario M3M 3B9
CANADA

Dr. A. D. Baddeley
Director, Applied Psychology Unit
Medical Research Council
15 Chaucer Road
Cambridge, CB2 2EF
ENGLAND

Defense Technical Information Center
Cameron Station, Bldg. 5
Alexandria, VA 22314 (12 cys)

Dr. Judith Daly
Cybernetics Technology Office
Defense Advanced Research Projects Agency
1400 Wilson Blvd
Arlington, VA 22209

Dr. M. Montemerlo
Human Factors & Simulation Technology, RTE-6
NASA HQS
Washington, D.C. 20546

Dr. Jesse Orlansky
Institute for Defense Analyses
400 Army-Navy Drive
Arlington, VA 22202

Dr. Robert G. Pachella
University of Michigan
Department of Psychology
Human Performance Center
330 Packard Road
Ann Arbor, MI 48104

Dr. T. B. Sheridan
Department of Mechanical Engineering
Massachusetts Institute of Technology
Cambridge, MA 02139

Dr. Arthur I. Siegel
Applied Psychological Services, Inc.
404 East Lancaster Street
Wayne, PA 19087

Dr. Harry Snyder
Department of Industrial Engineering
Virginia Polytechnic Institute and State University
Blacksburg, VA 24061

Dr. W. S. Vaughan
Oceanautics, Inc.
422 6th Street
Annapolis, MD 21403

Dr. Robert T. Hennessy
NAS - National Research Council
JH #819
2101 Constitution Ave., N.W.
Washington, DC 20418

Dr. Gershon Weltman
Perceptronics, Inc.
6271 Variel Avenue
Woodland Hills, CA 91364

455:ECG:716:maf
81u455-163

Dr. Robert Williges
Human Factors Laboratory
Virginia Polytechnical Institute
and State University
130 Whittemore Hall
Blacksburg, VA 24061

Dr. Alphonse Chapanis
Department of Psychology
The Johns Hopkins University
Charles and 34th Streets
Baltimore, MD 21218

Dr. James H. Howard, Jr.
Department of Psychology
Catholic University
Washington, D.C. 20064

Journal Supplement Abstract Service
American Psychological Association
1200 17th Street, N.W.
Washington, D.C. 20036 (3 cys)

Dr. Edward R. Jones
Chief, Human Factors Engineering
McDonnell-Douglas Astronautics
Company
St. Louis Division
Box 516
St. Louis, MO 63166

Dr. Richard W. Pew
Information Sciences Division
Bolt Beranek & Newman, Inc.
50 Moulton Street
Cambridge, MA 02138

Dr. David J. Getty
Bolt Beranek & Newman
50 Moulton Street
Cambridge, MA 02138

Dr. Douglas Towne
University of Southern California
Behavioral Technology Laboratory
3716 S. Hope Street
Los Angeles, CA 90007

Dr. A. K. Bejczy
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, CA 91125