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7/25/68

COMPARISON OF SINGLE-FUNCTION AND FOUR-FUNCTION SWITCHES ACROSS TWO LEVELS OF STIMULUS AND RESPONSE ALTERNATIVES

A THESIS

Presented to

The Faculty of the Division of Graduate Studies and Research

by

Gerald Gordon Birdwell

In Partial Fulfillment

of the Requirements for the Degree

Master of Science in Psychology

Georgia Institute of Technology

November, 1972

COMPARISON OF SINGLE-FUNCTION AND

FOUR-FUNCTION SWITCHES ACROSS TWO

LEVELS OF STIMULUS AND RESPONSE ALTERNATIVES

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ACKNOWLEDGMENTS

Special thanks are extended to Dr. E. Jo Baker, who in her capacity as thesis advisor contributed generously of her time, enthusiasm, and competent advice. Thanks are also due to the other members of the thesis committee, Dr. C. V. Riche, H. Bredendieck, and A. F. Beckum. Mr. Beckum replaced Mr. Bredendieck on this committee when Mr. Bredendieck was unable to participate in the author's oral examination due to a prior travel commitment.

The advice, assistance, encouragement, and support of Drs. G. D. Baskett, W. W. Ronan, and M. C. Payne, and the critical review of portions of this thesis by Drs. M. J. Marr, M. C. Payne, and A. D. Smith, are also greatly appreciated.

The author wishes to express special thanks to his parents for their understanding, encouragement, and moral and financial support during this project.

This thesis is dedicated to the author's girl friend, Miss Jeri Lynn Davis, who gave several months of her time in data recording and transcription and whose encouragement and support were invaluable.

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SUMMARY

Ensembles of four-function switches were evaluated relative to ensembles of single-function switches across number of stimulus and response alternatives by means of the following performance measures: control activation time (CAT), latency, movement time (MT), information transmission rate (ITR), and errors. The single-function switches were found to be superior, in terms of CAT and ITR, at the four-alternative level. However, no statistically significant differences were found at the eight-alternative level.

Within performance measures (CAT, latency, MT) conclusions regarding the relative efficiency of ensembles were independent of whether the mean or the median was used to summarize individual subjects' response distributions. It was suggested that this outcome was due to the relative consistency of the positive skew found across ensembles, and that this might be typical of choice reaction time distributions in general.

Large variation in MT across ensembles led to the hypothesis that, despite instructions and payoff designed to separate CAT into non-overlapping components of information processing time (measured by latency) and execution time (measured by MT), the experiment had produced ensemble-specific amounts of overlap. The hypothesis was supported by an intrasubject latency-MT correlation analysis and by an equivalent keypress analysis.

Examination of the empirical relations between the performance measures indicated that, for the present conditions, latency and MT were poor predictors of CAT but that, within alternative levels, ITR was a good predictor of CAT. The finding regarding latency was felt to be particularly significant because latency (elapsed time from stimulus onset to the beginning of a response) is widely treated as though it were congruent with or at least parallel to CAT (elapsed time from stimulus onset to the completion of a response). It was recommended that any conclusions about CAT be based on direct measurements of CAT rather than on questionable inferences from latency measurements.

An informal model was proposed which accounted for the ensemble-specific overlap between latency and MT in terms of response strategies.

CHAPTER I

INTRODUCTION

The increasing complexity of certain man-machine tasks, such as air-traffic control and spacecraft navigation, has emphasized the need to optimize the interface between man and machine as a means of increasing overall system performance. The present investigation is concerned with one aspect of this interface, namely, the effect of response devices (i.e., controls) on system performance.

With respect to controls, the trend has been for increased task complexity to dictate the inclusion of additional control elements (i.e., physically manipulable pushbuttons, knobs, levers, . . .) with a resultant increase in the overall size of the control panel and a decrease in the discriminability of individual control elements. Each of these changes has had a deleterious effect on system performance, especially in speeded tasks (Crossman, 1953; Siegel, Schultz and Lanterman, 1963; Schlesinger, 1964). Thus the goals of control design have come to include:

1. increasing the ratio of control functions to control elements,
2. simplifying control devices, both conceptually and in terms of the number of elements that must be manipulated, and

3. reducing the overall size of control devices, an especially important consideration where space is a problem.

One type of device that appears to satisfy these goals is the multiplex (i.e., multiple function) unit which assigns control of two or more functions to each element that must be manipulated by an operator. Control of the different functions is achieved by the manner in which the control element is moved. Available movements include: left-or-right displacement, up-or-down displacement, in-or-out displacement, clockwise-or-counterclockwise rotation, and various combinations of these movements. Although joysticks and other quantitative controls might be included within this classification, the present focus is limited to discrete, momentary-contact switches.

The most serious limitation to the general use of multiplex switches is that each function cannot be operated totally independent of the other functions. Specifically, the inherent design of the multiplex switch prevents the simultaneous operation of both functions from any axis of displacement or rotation. An N-function multiplex switch permits the simultaneous operation of, at most, $\frac{N}{2}$ functions, each positioned on a separate axis. Thus the suitability of a multiplex switch depends, in part, upon the nature of the functions that are to be controlled. The multiplex switch is suitable for use in systems where no functions require simultaneous operation, or where any functions which do require simultaneous operation can be positioned on separate axes.

A special case of the latter occurs when mutually exclusive functions are paired onto the same axes.

The previous "suitability" consideration refers to the ability of the multiplex switch to effect control of all desired combinations of functions. A second "suitability" consideration is concerned with the quality of the control that is exercised, in terms of such factors as speed and accuracy of operation. This consideration raises the question of how performance would be affected by the substitution of an array of $\frac{X}{N}$ N-function multiplex switches for an array of X simple switches.

Siegel, Shultz, and Lanterman (1963) included a comparison of two rows of 8 single-throw switches with one row of 8 double-throw switches in their study of several factors involved in control activation. Before the beginning of a trial, each of their three subjects was informed which of the following alternatives would be correct:

1. Row A, all 8 switches up,
2. Row B, all 8 switches down,
3. Row C (double throw), all 8 switches up, or
4. Row C (double throw), all 8 switches down.

A trial was begun by a warning light which the subject extinguished before carrying out the prespecified control activities. The only time measure which was recorded and reported was trial time, specifically, the elapsed time from the activation of the first switch through the activation of the 8th switch in the row. Unfortunately, trial time was solely a measure of the collective movement time for the parallel activation of 7 adjacent switches, devoid of perception and decision time. Thus the finding of a "small but statistically significant" difference, favoring the single-throw switches (2.43 seconds versus 2.28 seconds per trial of 7), has little relevance in assessing the relative empirical efficiency of the two types of controls.

The essential time measure for an assessment of relative control efficiency is control activation time (CAT) in a choice reaction task, i.e., the elapsed time from the onset of a stimulus to the completion of control activation. This measure is equivalent to the time needed by an operator in an applied task to perceive a signal, to decide on the appropriate response, and to execute the response. Any time measure that excludes information processing time (i.e., perception time and decision time) has little value toward predicting applied task performance where these factors operate.

In order to be able to identify the source of any measured CAT differences, it is desirable to partition CAT into measures of (a) processing performance time (i.e., the time cost of all mental processing preparatory to control activation in a choice reaction time task) and (b) execution (or movement) performance time. Such a partition can be attempted by measuring independently latency (elapsed time from stimulus onset to the beginning of a response) and movement time (elapsed time from the beginning of a response to the completion of the control activation). The validity of inferring that latency measures total processing performance time and that movement time (MT) measures only minimum required execution performance time depends on the degree to which the experimental situation yields separability of these components. For example, if a movement is begun while decision is still incomplete, then measured latency is less than total processing time, and concomitantly, measured MT is likely to be greater than minimum required execution time. Thus, if separation of the components is desired, a necessary condition is that the experiment be suitably designed with regard to instructional set (e.g., "Don't begin a movement until you have decided which response you will make") and/or payoff (e.g., "The shorter your MT, the greater your payoff") (Snodgrass, Luce, and Galanter, 1967).

If the desired partitioning is accomplished, the processing time component serves as a basis for determining the relative processing efficiency of various control ensembles, all other factors being equal. Similarly, the execution time component serves as a basis for determining the relative execution efficiency of various control ensembles, all other factors being equal. Whether or not partitioning is accomplished, CAT serves as a basis for determining the relative overall efficiency of various control ensembles, all other factors being equal.

The qualified "all other factors being equal" is mandatory (although unattainable in the strictest sense) if decisions regarding the relative efficiencies of controls are to be based on any of these time measures. It has been shown that the processing time portion of CAT is a complex measure which may be affected by many variables, such as: (a) receptor systems involved (Elliot and Louttit, 1948; Canfield, Comrey, and Wilson, 1949; Leob and Hawkes, 1961; Bliss, Townsend, Crane, and Link, 1965; Swink, 1966); (b) uncertainty regarding sensory modality, e.g., whether the next signal will be auditory, visual, tactual, . . . , (Kristofferson, 1965); (c) the nature of the stimulus within a sensory modality, e.g., a color sample versus the printed name of the color sample in a visual task (Cattell, 1947, as reported in Smith, 1968; Broadbent and Gregory, 1962; Morin, Konick, Troxell, and McPherson, 1965; Chase and Posner, 1965; Garner, 1970); (d) the number of stimulus alternatives (Hick, 1952; Hyman, 1953; Brainard, Irby, Fitts, and Alluisi, 1962; Lamb and Kaufman, 1965; Broadbent and Gregory, 1965); (e) the number of response alternatives (Crossman, 1953; Bricker, 1955; Wiggins, 1957; Morin and Forrin, 1963; Schlesinger, 1964; (f) the probability of occurrence of each stimulus (Hyman, 1953; Fitts, Peterson, and Wolpe, 1963; Favreau, 1964; La Berge and Tweedy, 1964; Lamb and Kaufman, 1965); (g) temporal uncertainty (Klemmer, 1957 b); (h) the probability of occurrence of each response (Dillon, 1966); (i) the sequential dependencies of stimuli (Hyman, 1953); (j) the repetition of stimuli <u>and</u> responses (Bertelson, 1961, 1963), the repetition of stimuli or responses (Bertelson, 1965), and the influence upon repetitions of the intertrial interval (Bertelson and Renkin, 1966; Williams, 1966); (k) stimulus discriminability (Garner and Hake, 1951; Crossman, 1955; Thurmond and Alluisi, 1963; Sternberg, 1964; Chase and Posner, 1965; Garner, 1970); (l) value of particular stimuli (Fitts, unpublished, reported in Smith, 1968; La Berge, 1964); (m) the mapping of stimuli onto responses in terms of the ratio of stimuli-to-responses (Posner, 1964; Fitts and Biederman, 1965) and the preceptual and conceptual nature of the mapping (coding) scheme (Rabbitt, 1959; Broadbent and Gregory, 1962; Pollack, 1963; Posner, 1964; Fitts and Biederman, 1965; Smith, 1968); (n) stimulus-response (S-R) compatibility (Fitts and Seeger, 1953; Fitts and Deininger, 1954; Fitts, 1959; Fitts and Switzer, 1962; Alluisi, Strain and Thurmond, 1964; Fitts and Biederman, 1964); (o) long-term practice and/or relevant transfer (Mowbray and Rhoades, 1959; Hanes and Rhoades, 1959; Seibel, 1963; Neisser, Novick and Lazar, 1963); and (p) the set, particularly regarding the speed-accuracy trade-off, imparted to the subject by instructions (Hick, 1952; Howell and Kreidler, 1963; Fitts, 1966) and by selective payoff (Snodgrass, Luce, and Galanter, 1967; Fitts, unpublished, reported in Smith, 1968).

It has also been shown that the MT portion of CAT is affected by many other types of variables such as: (a) the specific effectors used, for example, whether foot, jaw, arm, hand, or eye muscles or muscle action potentials are used to effect control (Hathaway, 1935; Seashore and Seashore, 1941; Stark, Vossius, and Young, 1962; Barlow, 1964; Wargo, 1967) and including such fine distinctions as which specific finger is used (Dvorak, Merrick, Dealey, and Ford, 1936; Kinney and Riche, 1962) and which chords of two or more fingers are used in simultaneous keypress (Ratz and Ritchie, 1961; Seibel, 1961); (b) the alternative responses within the response repertoire of a given situation (Kinney and Riche, 1962; Kornblum, 1965); (c) the physical parameters of the response device, such as the amount of movement distance (Brown and Slater-Hammel, 1948; Wehrkamp and Smith, 1952; Harris and Smith, 1954; Wargo, 1967), the precision with which the movement must be terminated (Fitts, 1954; Fitts and Peterson, 1964), and the amount of force required for control activation (Stump, 1952; Klemmer, 1957 a); (d) the orientation of the response device in relation to the operator (Stump, 1952); (e) the direction of movement of the control element/s (Stump, 1952; Loveless, 1962); (f) the discriminability of the control elements and/or positions of the elements (Fitts, 1947; Fitts and Crannell, 1953; Fitts, 1954; Bahrick, 1957; Bahrick and Noble, 1961; Garner, 1962; Fitts, 1964; Fitts and Posner, 1967); and (g) long-term skill practice (Snoddy, 1926; Crossman, 1959). Thus, the validity of attributing measured differences in CAT to differences in the efficiency of the control devices depends upon the experimenter's success in controlling for the above mentioned variables.

Moreover, in addition to the time measures, there remains another major criterion measure, that is, the proportion or degree of response accuracy. In fact, the value of any measure of choice response time exists only in relation to a concomitant measure of response accuracy. The human operator's demonstrated ability to trade speed of responding for accuracy of responding (Hick, 1952; Howell and Kreidler, 1963; Fitts, 1966) renders particularly suspect any conclusions regarding the comparative efficiency of different types of controls based upon either time or accuracy measures considered alone.

When both individual differences and set for speed versus accuracy of responding are controlled, a high positive correlation between speed and accuracy is usually found to exist across different experimental ensembles, presumably resulting from the effect on both speed and accuracy of the efficiency of the neural transformations required by each ensemble (Fitts, 1959). This means that most of the previously mentioned variables which affect processing time are also likely to affect accuracy of responding. Therefore, the control of these factors is doubly significant in the empirical assessment of control efficiency.

The present experiment was designed to meet two objectives:

1. An empirical assessment of the efficiency (measured by CAT and errors) of 4-way multiplex switches relative to functionally equivalent ensembles of simple switches, and

2. A theoretical assessment of the manner in which this exam-

ple of multiplexity affects performance, specifically an assessment of (a) the relative conceptual difficulty (measured by latency) and (b) the relative performance difficulty (measured by MT) of the two switch types.

Specifically, the present experiment manipulated control types and the number of stimulus and response alternatives while it attempted to control the remainder of the previously mentioned variables. The primary tactic for control was to equate all possible features of the various experimental conditions. Where it was impossible to equate features (e.g., S-R mapping, symbolic labeling of switch functions, . . .), an attempt was made to balance the overall effect each would have on performance, in order to minimize the probability of consistent bias. The procedures used in attempting to control the previously mentioned variables will be elaborated in the following chapter.

CHAPTER II

METHODS

Subjects

Forty-eight color-normal subjects were recruited from undergraduate psychology classes at the Georgia Institute of Technology. They received extra class credit for their participation. For additional motivation the subjects competed for $5 prizes which were awarded to the best performer in each experimental condition. Subjects were assigned to experimental conditions on the basis of the order in which they volunteered. The considerable equipment modification which was required to change from one experimental condition to the next dictated that each condition be run to completion before the next condition was begun. The temporal order of experimental conditions was:

1. 8 simple switch condition, S(8),
2. 4 simple switch condition, S(4),
3. 2 4-way switch condition, F(8),
4. 1 4-way switch condition, F(4).

Subjects did not know for which condition they were volunteering.

Apparatus

Booth

The experimental booth constructed for the experiment had a horizontal surface at 29-1/4 inches on which was located the Home Key (HK). An opening at the intersection of the horizontal surface and the vertical back surface (which the subject faced) accepted the control ensembles for the different experimental conditions. Angled vertical sides prevented visual distraction of the subjects.

An electromechanical shutter with a 1-1/2 inch aperture was positioned on the vertical surface at the approximate eye level of a typical seated subject (Dreyfus, 1967). A stimulus disc located on the back side of the booth facilitated the silent rotation of desired stimuli into position behind the shutter blade, prior to the opening of the shutter.

A removable label panel mounted midway between the shutter and the response ensemble presented to the subject's view a symbolic representation of the correct response for each possible stimulus. A different panel was used for each experimental condition. The appropriate panel was constantly present during an experimental session, and was positioned to facilitate the subjects' reference to it with minimum distraction from the other elements of the task. Functionally, these panels paralleled the symbolic labeling frequently used on control devices to portray the function or operating pattern of the device. For this experiment, however, the labeling appeared on the panel instead of on the control element itself. This modification was necessary for clarity and for uniformity across functionally different response ensembles.

Speakers located above the subject's head were used to present the prerecorded instructions and then to supply white noise for sound masking. A wide-angle peephole enabled the experimenter to monitor the adequacy with which the subject followed instructions (e.g., correct use of HK). To prevent shadow from the edge of the shutter aperture from falling on the recessed stimulus sample, an adjustable fluorescent lamp using "Daylight" tubes was positioned by the experimenter immediately above the seated subject's head.

Instrumentation

Five Hunter Klockounters, a response monitoring lamp array, and an impulse counter were located in an adjoining room. Two of the timers, set to millisecond accuracy, measured latency (the time to lift from HK) and CAT (the time to complete the first response) for each trial. The other timers, operating cumulatively, measured total session time spent (1) in latency, (2) in CAT, and (3) in total time off HK. The lamp array indicated which response the subject completed first on each trial. The impulse counter measured the total number of responses the subject completed during a session so that the number of multiple responses could be determined. (Multiple responses were penalized (see Appendices 2, 3, and 4) in order to discourage subjects from responding prematurely and then "correcting" erroneous initial responses.)

Stimuli

Colors were selected as stimuli in order to create tasks having neutral S-R compatibility, i.e., tasks neither taking advantage of strong predispositional tendencies nor violating them. This neutrality was sought in order to prevent compatibility from confounding any effects specific to the response devices being evaluated. Specifically, it was assumed that the subjects would not bring to the experiment strong predispositions toward associating color samples with response positions. To further assure the equality of S-R compatibility across the functionally distinct response ensembles, the assignment of colors to response positions was randomized across subjects.

An additional *a priori* requirement was that the elements of the stimulus alphabet be equally discriminable. The 8-element color alphabet developed by Conover and Kraft (1959) was selected to meet this requirement. However, pilot data revealed that in the present experimental context the Conover and Kraft colors (Set A) were not equally discriminable. Munsell 1R5.06/10.3 was involved in 46 per cent of all errors, and substitutions between this color and the spectrally adjacent color, Munsell 2.5RP4.90/9.5, accounted for 39 per cent of all adjacent substitution errors. The alphabet finally selected consisted of Conover and Kraft Set A with Munsell 1R5.06/10.3 replaced by Colormatch 203.

The 8-element alphabet was then divided into two spectrally adjacent 4-element subsets, A and D, each maintaining the level of discrimination difficulty of the total alphabet (Appendix 1). Random assignment of each subset to half of the subjects in each 4-alternative condition yielded for each switch type an A-subset subcondition and a D-subset subcondition.

The shutter surround which visually bordered each color sample during a trial was painted a color matched to Munsell N 5/ .

Stimulus Order

As previously mentioned, the quest for neutrality of S-R compatibility across conditions dictated that the assignment of color stimuli to response positions be randomized across subjects. However, known sequential and repetition effects dictated that certain features of the response (and stimulus) order be identical across conditions. Thus stimuli were presented so that:

(a) response order for each subject within a condition was identical, and

(b) response order across all conditions was random except as constrained by the following considerations:

 (1) each position occurred equally often within every 24-trial block;

 (2) 3 doubles (i.e., immediate repetitions) occurred within every 24-trial block; and

(3) no position occurred a second time as a double until each of the other positions had occurred as a double.

Response Ensembles

The response ensembles were (1) a radial arrangement of four simple switches, (2) a similar arrangement of eight switches, (3) one 4-way switch, and (4) two 4-way switches. All of the switches were of the spring-loaded, momentary-contact variety, with both an audible click and tactile feedback accompanying their operation. All of the simple switches required a downward keypress for operation. The 4-way switches were activated by an up, down, right, or left keypress.

Each element of the response ensembles equated the physical characteristics of (1) travel distance from HK to each element (9-1/2 inches) (see Appendix 1), (2) switch throw (1/8 inch), (3) switch resistance (7 ounces), (4) feedback click, and (5) size and color of the control elements. The actual response surface on the simple switches was a 3/4-inch diameter white cylinder mounted onto a flat, black lever. The response surface for the 4-way switches was a 3/4-inch white spherical knob on the end of a flat, black lever. The distance between switches in both of the simple switch ensembles was constant at 2-3/8 inches. The distance between the two 4-way switch knobs was greater at 3-5/8 inches because these knobs had to be grasped and operated horizontally as well as vertically. In order to prevent accidental multiple keypresses, the 4-way switches were constructed so that only one position could be operated at a given time. Thus a multiple keypress could be accomplished only by returning the switch to the center position following the first keypress and then making an additional keypress.

Label Panels

The label panels were designed to maximize isomorphism between the panel and the response ensemble which it labeled.

For each radial arrangement of simple switches, the panel consisted of a radial arrangement of 3/4-inch round holes behind which were positioned color samples identical to the stimuli. The panels were painted to match Munsell N 5/, as was the shutter surround. The assignment of colors to positions was varied across subjects by varying the placement of the color samples behind the holes corresponding to the switch positions.

The layout of the vertically mounted label panel was designed so that from the eye position of the average seated subject, the radial arrangement of holes appeared to be concentric with the horizontally mounted radial arrangement of switches. Further, based upon pilot data, the holes were spaced so that to the average subject they appeared to be directly above the corresponding switch.

The label panel for the 4-way switch was similarly constructed, but of necessity, the symbolic arrangement was different. On the panel, directly above the round switch knob, was a smaller (1-1/2 inch) white spherical knob representing the switch knob. This symbolic knob was surrounded by four 3/4-inch holes, one each above, below, and horizontally on either side. Thus if red appeared when the shutter opened and the same red was found to the right side of the symbolic knob on the label panel, then the correct response was to press the switch knob to the right.

The label panel for the ensemble of two 4-way switches was similar with a symbolic knob located above each switch knob.

Procedure

General Design

Four main conditions were tested: simple switches with 4 stimulus and response alternatives, S(4); simple switches with 8 alternatives, S(8); a 4-way switch with 4 alternatives, F(4); and 4-way switches with 8 alternatives, F(8).

In addition to the general factorial design, the two conditions at the 4-alternative level were each composed of two subconditions identified by the 4-element stimulus subset employed. Twelve subjects were run for each main condition, six subjects for each subcondition.

The overall design matrix was:

	4 alt.	8 alt.
Simple	S (4) A ($\underline{n}$ = 6)	S (8) ($\underline{n}$ = 12)
	S (4) D ($\underline{n}$ = 6)	
4-way	F(4) A ($\underline{n}$ = 6)	F (8) ($\underline{n}$ = 12)
	F(4) D ($\underline{n}$ = 6)	

The temporal order of executing the conditions was S(8), S(4), F(8), F(4). Within S(4) and F(4) the stimulus subset order was random.

Task

Each subject was first tested for color vision with the Dvorine Pseudo-Isochromatic Color Plates under "Daylight" fluorescent illumination. Any subject making more than one error was rejected. The color-normal subject was then seated at the experimental booth where he received prerecorded task instructions. The subject was also given the printed text of the instructions to follow and/or review at the end of the recording.

The instructions explained the switches, the label panels, the use of HK, the stimulus order, the performance criteria defined by a scoring procedure, and the ($5) prizes to be awarded to the best scorer in each experimental condition (Appendices 2, 3, 4, and 5). Subjects were told that the stimulus order was random and that stimulus repetitions could occur. Subjects were not told of the constraints on stimulus order which prevented it being truly random.

The scoring procedure explained to the subject a rather detailed payoff function, which was repeated and elaborated upon. The purpose of this detailed scoring procedure was threefold:

(1) The competitive situation created by the scoring procedure, prizes, and the subjects' knowledge that earned scores would be posted in the psychology classrooms was felt to be

important in motivating the subjects for the lengthy repetitive task.

(2) The consequences of speed of responding and occurrence of errors were detailed in an attempt to elicit from the subject the desired speed-accuracy tradeoff function.

(3) The specific details of the scoring procedure were selected in an attempt to separate, in a measurable way, the relative effects on CAT of processing time and execution time. Secondarily, the payoff details were selected to maximize the sensitivity of latency as a measure of relative task difficulty.

Specifically, each subject was told that the lowest numerical score was "best" and that the earned score consisted of three additive components:

(1) average CAT,

(2) 1/10 average CAT times number of errors, and

(3) 1/2 average "total time off HK," (Appendices 2, 3, and 4).

The first two components were intended to shape the speed-accuracy tradeoff. The third component, plus the accompanying clarification, pointed out the payoff advantage of remaining on HK until a keypress decision was "relatively certain," moving rapidly to effect the response, and then quickly returning to HK. It was assumed then that the effect of (3) would be to make latency a measure of processing time, thus allowing a measure of movement time alone to be computed from the difference between CAT and latency. Further, the procedure was intended to sensitize latency as a measure of overall task difficulty by penalizing the process of lifting from HK immediately upon presentation of a stimulus and prior to completion of the decision process.

Session

The stimuli were manually initiated by the experimenter. The stimulus order was prearranged in such a manner that the correct response on any trial was the same for all subjects in a group despite the randomized assignment of stimuli to responses across subjects.

The latency timer, CAT timer, and lamp array were read and recorded manually for each trial by an assistant who was located in an adjoining room. The cumulative timers were read and recorded only at the completion of an experimental session. The intertrial interval was approximately twelve seconds.

A session consisted of 192 trials (204 for several early subjects) and lasted approximately fifty minutes. A brief rest interval of less than three minutes was given after trial 120. The subject was encouraged to stretch, walk down the hall, and/or get a drink of water at a nearby fountain.

The subject was given overt feedback (mean CAT) only at the conclusion of the experiment, although the appropriate label panel was always in view. At the completion of the session, the subject was also given a description of the purpose and procedure of the experiment, shown the working of the apparatus, and allowed to ask any questions. All scores were posted in the psychology classrooms and winners were announced approximately one week after the completion of each experimental condition.

CHAPTER III

RESULTS

On the basis of mean CAT per 24-trial block, calculated separately for each group (Appendix 6), trials 49-168 were selected as representing relatively flat performance plateaus. All further analyses were based on these trials.

The mean and median CAT were computed for each subject. In view of the consistent (47 of 48) finding of a larger mean than median, distribution analyses (Veldman, 1967, pp. 181-189) were performed independently on the CAT data of each subject. The results of these analyses (Appendix 7) indicated that for 42 of the 48 subjects, the probability that the CAT values in fact represented a symmetrical distribution was less than .05. For these asymmetrical distributions the median is more representative (than the mean) of the "most typical" CAT of a subject. However, by definition, the mean remains the summary measure most representative of a subject's overall CAT distribution.

Overall Analyses

On the basis of the above considerations, both mean and median CAT were independently analyzed along with information transmission rate (ITR). These summary measures for each subject are given in

Appendix 8. The group means of these measures are included in Table 1 and illustrated in Figures 1-3. The results of the independent two-way analyses of variance (switch type by number of alternatives) are summarized in Table 2.

For each of these measures, increasing the number of alternatives from 4 to 8 significantly decreased performance ($p < .05$). In no case was the overall effect of switch type significant, although the median CAT ($p = .0553$) just missed the minimum acceptable significance level of .05. For each measure, except median CAT, the inter-

Table 1

Group Mean Scores

Measure		S(4)	S(8)	F(4)	F(8)
CAT (in seconds),	mean	.6718	1.0079	.7662	.9847
	median	.6580	.9540	.7515	.9541
Latency (in seconds),	mean	.4139	.7616	.4006	.5601
	median	.4121	.7207	.4003	.5582
MT (in seconds),	mean	.2578	.2462	.3656	.4245
	median	.2325	.2113	.3408	.3785
ITR (in bits/second)		3.0678	3.1090	2.6546	3.1566
Number of Errors		.9167	1.6667	1.5833	1.0000
Latency-CAT correlation		.4503	.7675	.3916	.3819

Table 2

Results of Analyses of Variance Independently Performed on Mean CAT, Median CAT, ITR, and Error Data

Source	Measure	*F*
Switch Type	Mean CAT	1.9183
	Median CAT	3.7778 (p = .0553)
	ITR	5.1312*
	Errors	.0000
Number of Alternatives	Mean CAT	116.3011***
	Median CAT	107.2295***
	ITR	11.3218**
	Errors	.0344
Interaction	Mean CAT	5.2297*
	Median CAT	3.7643 (p = .0557)
	ITR	8.1495**
	Errors	2.2034

Note.--For each F, df = 1,44.

*$p < .05$.

**$p < .01$.

***$p < .001$.

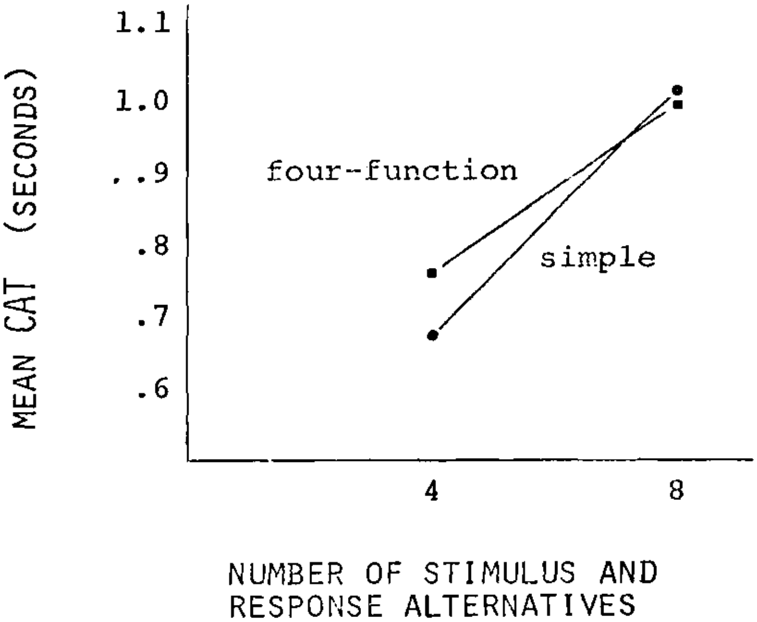

Figure 1. Mean CAT as a Function of the Number of Stimulus and Response Alternatives for Simple and Four-Function Switches.

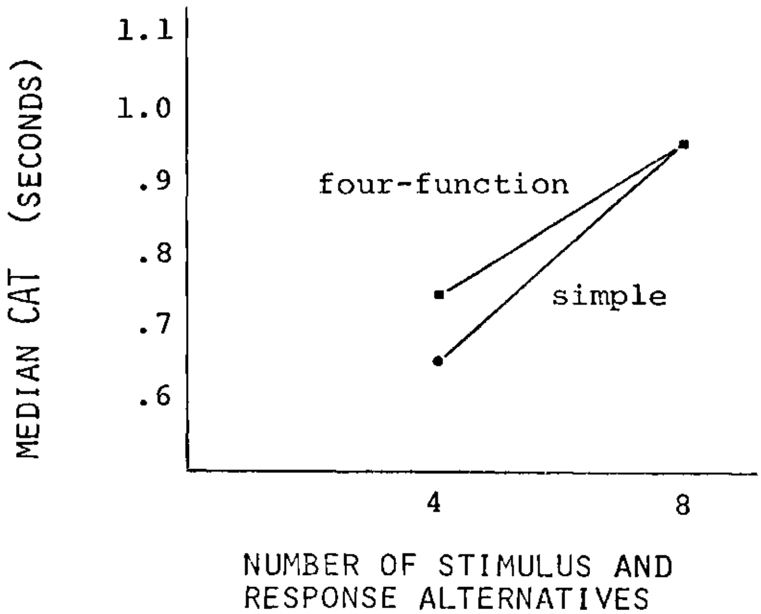

Figure 2. Median CAT as a Function of the Number of Stimulus and Response Alternatives for Simple and Four-Function Switches.

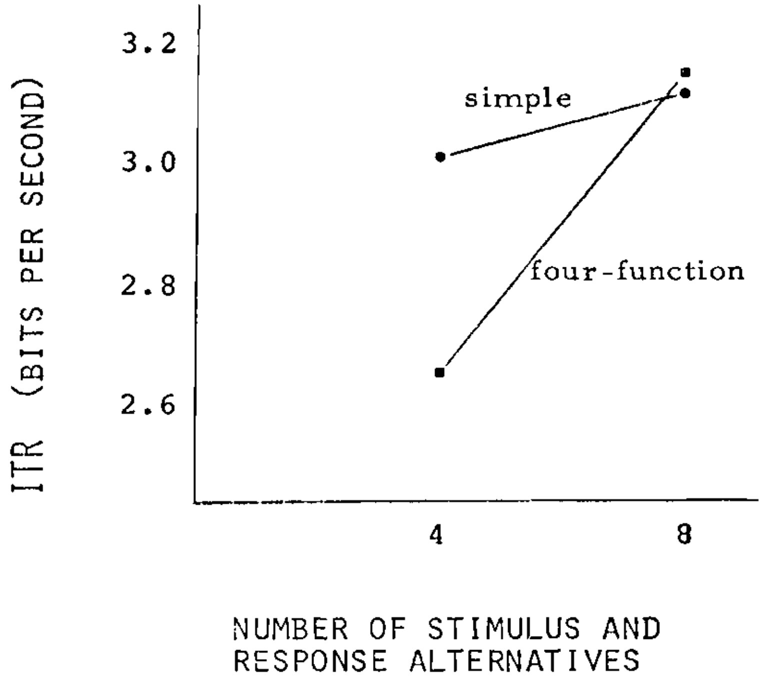

Figure 3. ITR as a Function of the Number of Stimulus and Response Alternatives for Simple and Four-Function Switches.

action was significant, with the median CAT again just missing significance (p = .0557).

Similar analyses of the number of errors, summarized in Table 2, revealed no significant effects.

Contrasts

A priori F tests were performed on the contrasts across switch types S(4) - F(4) and S(8) - F(8), and on the contrasts across the number of alternatives, S(4) - S(8) and F(4) - F(8). The results of these F tests using mean CAT, median CAT, and ITR are summarized in Table 3.

Table 3

Results of Contrasts Independently Performed on Mean CAT, Median CAT, and ITR Data

Contrast	Measure	*F*
"Switch Type"		
S(4) - F(4)	Mean CAT	12.864**
	Median CAT	11.947**
	ITR	17.463***
S(8) - F(8)	Mean CAT	.276
	Median CAT	.000
	ITR	.139
"Number of Alternatives"		
S(4) - S(8)	Mean CAT	78.638***
	Median CAT	74.717***
	ITR	.137
F(4) - F(8)	Mean CAT	39.515***
	Median CAT	35.824***
	ITR	18.465***

Note.--For each *F*, *df* = 1, 22.

*$p < .05$.

**$p < .01$.

***$p < .001$.

Each of the relevant contrasts showed a significant performance decrement with increases in the number of alternatives except for S(4) - S(8) using ITR, which showed no effect. The switch type contrasts showed that for all measures the simple ensemble was superior to the 4-way (multiplex) ensemble, at the 4-alternative level. However, again for all measures, the two switch types were not significantly different at the 8-alternative level.

Stimulus Subset (Color Effect) Analysis

Two-way analyses of variance of the subconditions at the 4-alternative level, classified by switch type and stimulus subset, were performed independently for each measure to determine whether the stimulus subsets differentially affected performance (Appendices 9 and 10). The mean CAT, median CAT, and ITR measures yielded significant effects only for switch type and the error data yielded no significant effects. Thus the stimulus subsets had no significant effect on these performance measures.

Latency and MT Analyses

Latency and MT measures were independently analyzed in an attempt to discover the bases of the differences in CAT across ensembles.

Overall. Mean latency and MT, and median latency and MT were computed (Table 1) and independently subjected to 2-way analyses of variance classified by switch type and number of alternatives, as summarized in Table 4. Group means for these measures are illustrated

Table 4

Results of Analyses of Variance Independently Performed on Latency and MT Measures

Source	Measure		F
Switch Type	Latency,	Mean	14.7174***
		Median	10.7864**
	MT,	Mean	48.8871***
		Median	43.2853***
Number of Alternatives	Latency,	Mean	82.0761***
		Median	77.3837***
	MT,	Mean	1.3398
		Median	.1553
Interaction	Latency,	Mean	11.2957**
		Median	8.0720**
	MT,	Mean	2.9753
		Median	1.9740

Note.--For each F, $df = 1,44$.

*$p < .05$.

**$p < .01$.

***$p < .001$.

in relation to CAT in Figure 4.

The analyses indicated that for each measure switch type was significant ($p < .01$). For mean and median latency, number of alternatives ($p < .001$) and the interaction ($p < .01$) were also significant. As can be seen in Figure 4, latency and MT are not consistently related to CAT, especially across switch types.

Contrasts. *A priori* *F* tests were performed on the contrasts across switch types, S(4) - F(4) and S(8) - F(8), and across number of alternatives, S(4) - S(8) and F(4) - F(8), for mean latency, median latency, mean MT, and median MT, independently. The results of these contrasts are summarized in Table 5. Mean and median latency measures showed significant differences in the S(4) - S(8), F(4) - F(8), and S(8) - F(8) contrasts. Mean and median MT measures showed significant differences only for the switch type contrasts, S(4) - F(4) and S(8) - F(8).

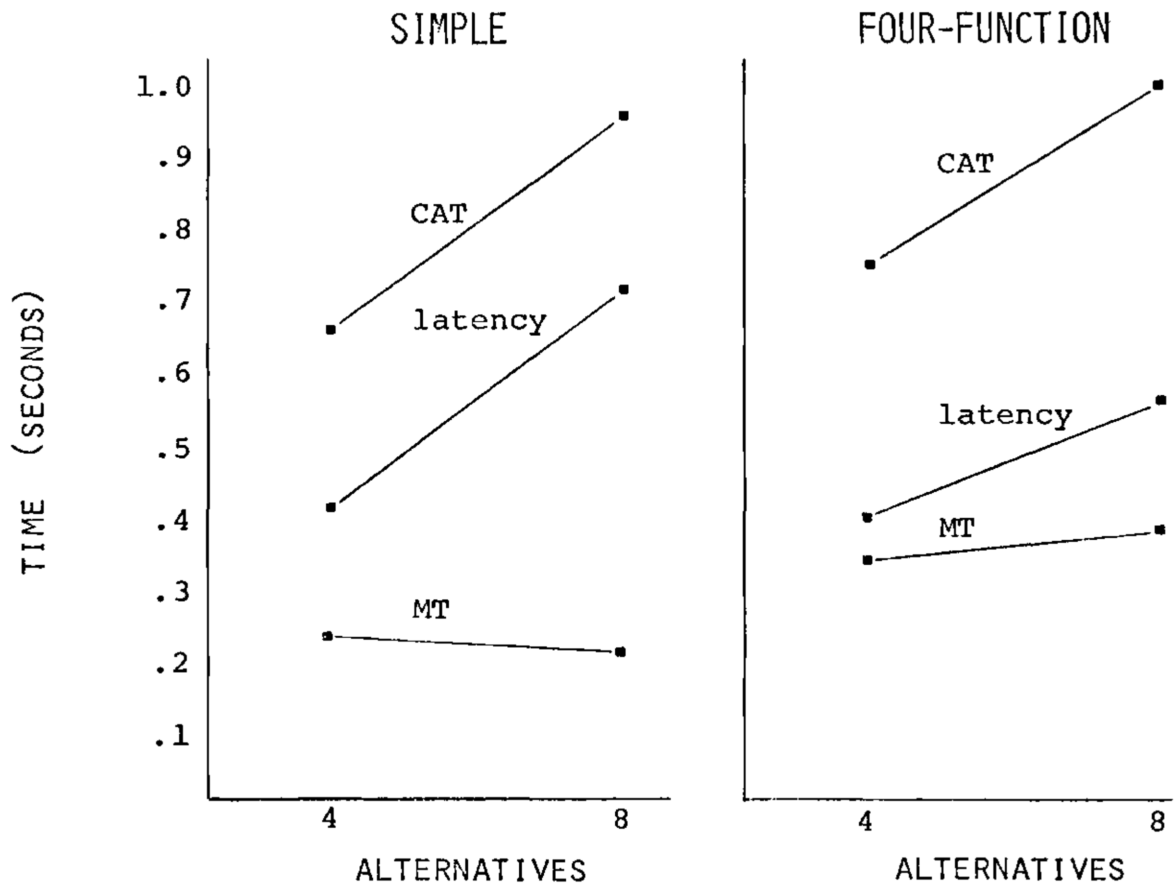

Figure 4. Comparison of Several Performance Measures (Median CAT, Median Latency, and Median MT) across Number of Stimulus and Response Alternatives for Ensembles of Simple and Four-Function Switches.

Table 5

Results of Contrasts Independently Performed
on Mean Latency, Median Latency, Mean MT, and Median MT

Contrast	Measure		F
"Switch Type"			
S(4) - F(4)	Latency,	Mean	.312
		Median	.220
	MT,	Mean	13.569**
		Median	12.109**
S(8) - F(8)	Latency,	Mean	15.818***
		Median	12.073**
	MT,	Mean	38.856***
		Median	35.632***
"Number of Alternatives"			
S(4) - S(8)	Latency,	Mean	71.483***
		Median	72.333***
	MT,	Mean	.332
		Median	1.169
F(4) - F(8)	Latency,	Mean	17.631***
		Median	16.672***
	MT,	Mean	2.741
		Median	1.036

Note.--For each F, $df = 1, 22$.

*$p < .05$.

**$p < .01$.

***$p < .001$.

CHAPTER IV

DISCUSSION

Rank Ordering of Dependent Variables and Measures

In order to clarify the empirical relations existing among the dependent variables (CAT, latency, MT, and ITR) and the summary measures (mean and median), the experimental ensembles were rank ordered, from best to worst, independently for each measure of each dependent variable, as shown in Table 6. The error measure, which showed no significant differences between ensembles, was excluded from the ranking. Within measures and/or dependent variables, each occurrence of nonsignificant differences between ensembles resulted in both ensembles being assigned the appropriate midrank.

Mean Versus Median

Both summary measures were independently analyzed so that conclusions could be based either on measures representing the most typical response (medians) or on measures best representing the overall response distribution (means). The consistency with which positively skewed CRT distributions are found recommends the use of the mean in applied problems where overall performance assessment is desired. However, for theoretical problems concerned with basic underlying processes, the argument that the small number of quite slow responses results from uncontrolled confounding (attention, motivation, distraction) recommends a measure such as the median which deemphasizes extreme values.

The present results demonstrate that the rank ordering of ensembles is in no case a function of which summary measure was employed. This is likely due to the relatively uniform positive skew seen across these distributions. However, such a positive skew is typical of choice reaction time distributions in general. Thus the concern over selection of a summary measure for choice reaction time distributions may be rather trivial in hypothesis testing applications, at least where the distributions are similarly skewed.

Table 6

Rank Order of Ensembles (Best to Worst)
on the Basis of Several Measures

Measure	S(4)	S(8)	F(4)	F(8)
Mean CAT	1	2	3-1/2	3-1/2
Median CAT	1	2	3-1/2	3-1/2
Mean Latency	1-1/2	1-1/2	4	3
Median Latency	1-1/2	1-1/2	4	3
Mean MT	1-1/2	3-1/2	1-1/2	3-1/2
Median MT	1-1/2	3-1/2	1-1/2	3-1/2
ITR	2	3	1-1/2	1-1/2

Dependent Variables

The rank ordering of ensembles is seen to be highly sensitive to the selection of the dependent variable which serves as the basis for the ranking.

ITR. The poor correspondence between CAT and ITR was not unexpected in view of the common finding (see Garner, 1962, pp. 90-93) that maximum ITR results from maximum stimulus uncertainty, which occurs here in Ensembles S(8) and F(8) because of their larger number of stimulus alternatives. It can be seen that within each level of number of alternatives, the correspondence between CAT and ITR is perfect. Thus it appears generally necessary to limit the use of the ITR measure to comparisons within levels of stimulus uncertainty even where, as in the present case, error rate is uniformly low across ensembles.

Further, Pollack and Gildner (1963) have questioned the usefulness of ITR or any other fixed speed-accuracy composite measure, recommending instead that where composite measures are desired, they should be constructed to reflect the relative values of speed and accuracy specific to the man-machine system under consideration. However, in theoretically-oriented comparisons of ensembles where specific speed and accuracy values are unavailable, the need for a fixed speed-accuracy composite measure seems to be well served by the widely used ITR measure, provided that comparisons are restricted to ensembles having equal numbers of stimulus alternatives.

Latency. The low correspondence between CAT and latency was unexpected, especially since the instructions and payoff had been designed to sensitize latency to task difficulty (measured by CAT) by penalizing both premature lifting from HK and slow movements. This finding is of considerable interest because latency is commonly used in the literature, without empirical validation, as though it corresponded perfectly with CAT. However, this analysis suggests that the relation between latency and CAT is contextually determined.

Extended Analyses

Intrasubject Latency - CAT Correlations

In order to determine to what extent the relation between group mean latency and group mean CAT reflected the relation within individual subjects, a Pearson product moment correlation between latency and CAT for Trials 49-168 was computed for each subject (Appendix 8). The group means of these correlations are included in Table 1. Distribution analyses (Veldman, 1967, pp. 181-189) performed independently on the correlation data for each group (Appendix 11) showed that for no group could the hypothesis be rejected that the sample had been drawn from a population of values having skewness = 0 and kurtosis = 0. The correlation data were then subjected to a 2-way analysis of variance classified by switch type and number of alternatives, as summarized in

Table 7. This analysis indicated that intrasubject correlation between latency and CAT was significantly affected by switch type ($\underline{p} < .001$), number of alternatives ($\underline{p} < .05$), and the interaction ($\underline{p} < .01$). These results support the previous analyses in demonstrating that the relation between latency and CAT is ensemble-specific in this experiment.

Table 7

Results of the Analysis of Variance Performed on Intraindividual Latency-CAT Correlations (Trials 49-168)

Source	$\underline{df}$	$\underline{F}$
Switch Type	1,44	13.5413***
Number of Alternatives	1,44	6.4857*
Interaction	1,44	7.3337**

*$\underline{p} < .05$.
**$\underline{p} < .01$.
***$\underline{p} < .001$.

Equivalent Keypress MT Analysis

The previous analyses suggest that the present experiment may not have unambiguously separated CAT into processing time and movement time. This suggestion is supported by the observation (see

Table 1) that latency for the conceptually more difficult F(8) is smaller than for S(8), coupled with the observation that MT for F(8) is almost twice as great as MT for S(8) despite the fact that all physical response parameters except direction of movement had been equated across ensembles.

In order to assess the possibility that direction of movement accounted for the large difference in MT across ensembles, subsets were formed of all trials in which the required physical response was virtually identical across ensembles. The subsets were composed of (1) the mean MT of all trials using either of the two centermost keys of S(4); (2) the mean MT of all trials using either of the two centermost keys of S(8); (3) the mean MT of all trials in which F(4) was pressed down; and (4) the mean MT of all trials in which either key of F(8) was pressed down (Appendix 11). The group means for MT on these physically equivalent keypresses are included in Table 8. A 2-way analysis of variance (Appendix 12) showed that the effect of switch type on MT was statistically significant ($p < .001$). This outcome, plus the striking similarity between overall MT and MT for identical keypresses (Table 8), asserts that direction of movement does not account for the large MT differences across ensembles.

It follows from these results, considered collectively, that despite the concentrated experimental attempt to functionally separate processing performance time (measured by latency) and minimum required execution time (measured by MT), the present experiment did not in fact accomplish such a partition.

Table 8

Group Mean MT for all Keypresses and for Physically Equivalent Keypresses

	S(4)	S(8)	F(4)	F(8)
MT for all keypresses (in seconds)	.2578	.2462	.3656	.4245
MT for physically equivalent keypresses (in seconds)	.2558	.2438	.3694	.4151

<u>Formation of Response Strategies: An Informal Model</u>

The contrasts performed with mean CAT, median CAT, and ITR demonstrate that under the conditions of this experiment simple switches are empirically more efficient than 4-way multiplex switches at the 4-alternative level but not at the 8-alternative level. The nonparallel rate of gain of information curves, shown in Figure 3 and verified by the statistically significant interaction between number of alternatives and switch type, demonstrate that the efficiency of 4-way switches increases relative to simple switches as the number of alternatives is increased. Since the multiplex switches were viewed as being conceptually more difficult, or at least less familiar to the present subjects, this is an unexpected result. Further research is needed to evaluate the effect of (1) extending the number of alternatives, (2) extending the amount of practice, and (3) increasing the examples of multiplexity (e.g., 2-way switches, 8-way switches).

The most interesting questions raised by the present results were: (1) What could account for the increase in the efficiency of 4-way switches (relative to simple switches) with number of alternatives? (2) What could account for the failure of instructions and payoff to empirically separate CAT into nonoverlapping components of processing time and execution time? (3) What could account for the ensemble specific correlations between latency and CAT when instructions and payoff were the same for all conditions? These questions take on added significance in view of the extensive effort that was taken to control all variables known to affect performance.

Close examination of the data suggests a tentative explanation which bears on all three questions. First, despite the uniform presentation of both explicit instructions and detailed payoff, different response strategies were apparently used by the different groups, as demonstrated by the nonparallelism of the various dependent variables across conditions and by the ensemble-specific latency-CAT correlations. The response strategies may be determined by the amount of overlap between processing and execution time that each ensemble allowed (by its physical design and experimental operation) and/or benefited from, in terms of overall performance. Logical analysis of the physical attributes of the ensembles suggests that CAT performance on some ensembles (e.g., F(8)) might benefit from a strategy of lifting from HK before the completion of response selection, whereas on others (e.g., S(8)) such a strategy might result in a negligible benefit or perhaps a liability. The key to the effect on CAT performance of lifting before the completion of response selection is the extent to which response selection can be combined with an efficient movement. For example, response selection may be coupled with an efficient movement in F(8) because the major portion of the movement is identical regardless of the terminal response. On the other hand, selection cannot be coupled with an efficient movement in S(8) because virtually the entire movement is specified by the appropriate response. A premature lifting in S(8) would result in a less efficient (i.e., overly lengthy) movement due to hovering in mid-air while the final selection was made, and/or backtracking from an inappropriate intermediate position to complete the correct response.

In order to assure that an efficient movement results, a subject operating:

(1) S(8) would need to complete response selection before leaving HK (i.e., make a choice from 8 alternatives),

(2) S(4) would need to complete response selection before leaving HK (i.e., make a choice from 4 alternatives),

(3) F(8) would need to select which switch was appropriate before leaving HK (i.e., make a choice from 2 alternatives),

(4) F(4) would need to make no selection before leaving HK, one switch being appropriate for all responses.

The potential penalty to CAT performance for premature lifting (i.e., the extra time necessary to complete selection and/or correct partially completed movements that would have been incorrect) would be greatest for S(8) because of the relatively large spatial range involved (15 inches), second for S(4) because of the reduced spatial range involved (7 inches), third for F(8) because only two closely spaced switches are involved, and least for F(4) with its single switch.

If these factors have in fact been operational, then the proportion of CAT spent in latency should be greatest for S(8), second for S(4), third for F(8), and least for F(4). This prediction is congruent with the empirical results, as seen in Table 9.

Table 9

Proportion of CAT Spent in Latency

Group	Mean Data	Median Data
S(8)	.76	.79
S(4)	.61	.62
F(8)	.57	.59
F(4)	.52	.53

These analyses considered collectively support the following hypotheses:

1. This experiment failed to functionally partition CAT into separate information processing and execution components, because the physical characteristics of the ensembles elicited response strategies differing essentially by the amount of overlap between processing and movement that each fostered, and

2. The multiplex (4-way) ensembles fostered more overlap than did the simple switches because they benefited more (in overall CAT performance) from the overlap than would the simple switch ensembles. However, further research is needed to determine (a) the mini-

mum execution time required by the ensembles, (b) the total amount of processing time required by the ensembles, (c) the amount of temporal overlap produced by the various conditions of this experiment, and (d) the amount of temporal overlap that would be produced by an experiment which did not instruct against or penalize overlap.

CHAPTER V

IMPLICATIONS

Generalization to Applied Tasks

Certain constraints which were inherent in the design of the present experiment may bear upon the appropriateness of any generalization to applied tasks. For example, the present study

1. studied each keypressing task in isolation from other performance,
2. examined only conditions having four and eight stimulus and response alternatives,
3. deliberately sought neutral S-R compatibility,
4. employed somewhat artificial instructions and payoff (as compared to applied tasks) which penalized temporal overlap between information processing and movement, and
5. imposed no memory requirements upon subjects.

An empirical evaluation is recommended for applied tasks which differ appreciably from the conditions of this study.

Interpretation of Other Research Findings

Separation of Processing Time and Execution Time

The present demonstration of apparent overlap between processing time and execution time, despite instructions and payoff specifically designed to achieve separation, makes somewhat suspect the results of any study which purported to measure total processing time by the empirical measurement of latency. Particularly suspect are any studies in which the response ensembles required subjects to make substantial amounts of movement, especially if an overt attempt were not made to achieve separation.

The present findings further suggest that overlap, if present with a given type of response device, is likely to be a decreasing function of the number of response alternatives offered. Thus the magnitude of the difference in processing time across two levels of uncertainty (i.e., number of alternatives) may previously have been consistently overestimated. Specifically, a response device which underestimates processing time because of overlap would be likely to underestimate processing by a greater amount at the 4-alternative level than at the 8-alternative level, thus yielding a consistently inflated measure of the difference between levels.

Thus the first consideration questions the magnitude of measured processing time, while the second consideration questions the magnitude of the measured differences in processing time across levels of uncertainty. These considerations are in need of empirical evaluation. If verified, they might help explain the break in the rate of gain of information curves which typically occurs at about 3 bits (8 alternatives).

Appropriateness of Measures

The present results serve to emphasize the rational conclusion that latency can provide a valid measure of total processing time (perception time plus decision time) only if experimental procedures succeed in empirically partitioning CAT into nonoverlapping components of processing time and execution time.

Further, the results of the rank ordering of the ensembles based independently on the various dependent variables (see Table 6) suggest that latency can be a good predictor of relative CAT performance among ensembles only where (1) latency is a valid measure of total processing time and where (2) minimum required execution time is virtually constant across ensembles. Significant differences in execution time across ensembles may be sufficient to invalidate the prediction of CAT based solely on the latency measure of processing time.

Thus the widespread use of latency as a measure of total processing time, independent of movement time (which may vary across effector organs, muscles, direction of movement, . . .), is questioned. It is suggested that a more valid measure of total processing time independent of movement time would be obtained by subtracting from CAT the measured movement time in a similar simple reaction time task, which could not be contaminated by overlap.

Likewise, the use of latency as a predictor or CAT for applied tasks is questioned. It is suggested that where a measure of CAT performance is desired, it should be obtained directly.

APPENDIX I

CROSS-SECTION OF EXPERIMENTAL BOOTH

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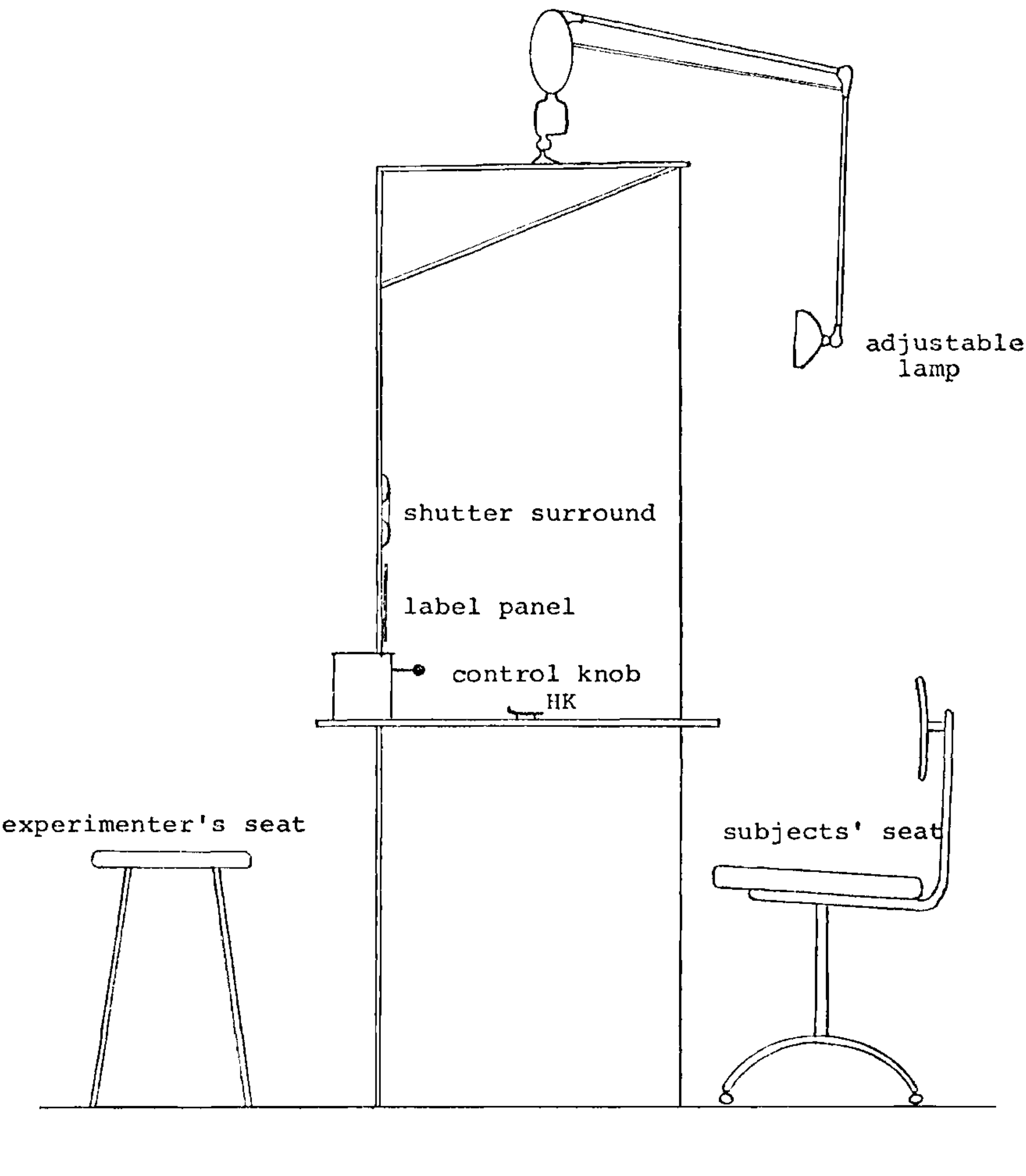
CROSS-SECTION OF EXPERIMENTAL BOOTH



APPENDIX 2

STIMULI

APPENDIX 2

STIMULI

Conover and Kraft	Present Stimulus Set	Stimulus Subset A	Stimulus Subset D
M[1] 1R 5.06/10.3	C[2] 203	C 203	
M 9.5R 5.93/11.5	M 9.5R 5.93/11.5	M 9.5R 5.93/11.5	
M 2Y 7.12/11.6	M 2Y 7.12/11.6	M 2Y 7.12/11.6	
M 5GY 6.48/8.3	M 5GY 6.48/8.3	M 5GY 6.48/8.3	
M 10G 4.88/6.8	M 10G 4.88/6.8		M 10G 4.88/6.8
M 6B 4.00/7.0	M 6B 4.00/7.0		M 6B 4.00/7.0
M 1.5P 3.74/11.1	M 1.5P 3.74/11.1		M 1.5P 3.74/11.1
M 2.5RP 4.90/9.5	M 2.5RP 4.90/9.5		M 2.5RP 4.90/9.5

[1] Munsell

[2] Colormatch

APPENDIX 3

TEXT OF THE RECORDED AND PRINTED INSTRUCTIONS EMPLOYED WITH ENSEMBLES S(4) AND S(8)

APPENDIX 3

TEXT OF THE RECORDED AND PRINTED INSTRUCTIONS EMPLOYED WITH ENSEMBLES S(4) AND S(8)

This is a human factors experiment designed to learn something about the nature of human performance that can be expected with different types of control devices. You will only use one type of control; later the performance of all the subjects using this same control will be compared with the performance of groups using other controls.

You will receive grade credit in your psychology class for cooperative participation in this experiment, irrespective of your performance. However, for interest and incentive, a $5.00 prize will be given to the subject using each type of control who earns the best score. The way you are scored will be explained as soon as the task is described.

The task is a simple one, but the object is to respond as fast as you can without making mistakes. First, sit comfortably at the booth. Put your preferred hand on the home key and hold it down firmly. Put your other hand in your lap. You will use only your preferred hand throughout this experiment. Now look at the black shutter in front of you. When the shutter opens, a color sample will be seen which is the same as one of the colors on the panel just under the shutter. The placement of colors on the panel indicated which key should be pressed when the shutter opens. As soon as you have decided which key is the correct one to press, leave home key, press the chosen key, and then return as fast as you can to home key. Do not press more than one key, even if you make an error. Pressing more than one key will count as a double error, even if one is correct.

Shortly after you have returned to home key, the shutter will open again, and the cycle will be repeated.

---Each color will be presented the same number of times.

---The order of occurrence of the colors will be random. Thus it is possible for the same color to appear two or more times in a row.

White noise will be presented throughout the experiment to prevent equipment sounds and other extraneous noises from distracting you.

And now to explain the scoring procedure. First of all, the 'best' score is the lowest score, and the score is composed of three components added together. The first component is your average control activation time, that is, the average time from the opening of the shutter until you press a key. The second component is a penalty for errors, specifically, the addition of 1/10th of your average control activation time for each error. The final component is 1/2 of your average time off home key.

To repeat, remembering that the lowest score is best, your score is the sum of your average control activation time, plus an additional 1/10th of this control activation time for each error, plus 1/2 of the average time you are off home key on each trial.

Therefore, in order to achieve the best score you should: (1) respond accurately. Ten errors add to your score a component as large as your control activation time. Remember also that pressing more than one key on a trial always counts as a double error even if one of the keypresses is correct; and (2) remain on home key until you are relatively sure which key to press. Move rapidly to press it. Then return as fast as you can to home key. This procedure minimizes both control activation time and the total time you are off home key.

Finally, the instructions have been presented in this way so that every subject receives identically the same instructions. All the information necessary to perform the experiment is given here, so please do not ask additional questions at this time. Any questions you may have about the nature of the experiment will be gladly answered at the end of the experiment, so please wait until then.

You may now take a few moments to look over the printed instructions. You may also make some practice keypresses to get the 'feel' of the equipment if you so desire.

Note that the experiment will last approximately 50 minutes with a rest break at about the midway point.

APPENDIX 4

TEXT OF THE RECORDED AND PRINTED INSTRUCTIONS EMPLOYED WITH ENSEMBLE F(4)

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TEXT OF THE RECORDED AND PRINTED INSTRUCTIONS EMPLOYED WITH ENSEMBLE F(4)

This is a human factors experiment designed to learn something about the nature of human performance that can be expected with different types of control devices. You will use only one type of control. Later the performance of all the subjects using this same control will be compared with the performance of groups using other controls.

You will receive grade credit in your psychology class for cooperative participation in this experiment, irrespective of your task performance. However, for interest and incentive, a $5.00 prize will be given to the subject using each type of control who earns the best score. The way you are scored will be explained as soon as the task is described.

The task is a simple one, but the object is to respond as fast as you can without making mistakes. First, sit comfortably at the booth. Put your preferred hand on the home key just behind the lip and hold it down firmly. Put your other hand in your lap. You will use only your preferred hand throughout this experiment. Now look at the black shutter in front of you. When the shutter opens, a color sample will be seen which is the same as one of the colors on the plate just under the shutter.

The placement of the colors on the plate indicates the direction in which the key should be pressed--either up, down, right, or left. As soon as you have decided which keypress to make, leave home key, make the chosen keypress, and then return as fast as you can to home key. Do not make more than one keypress on a trial, even if you make an error. Making more than one keypress will always count as a double error, even if one is correct.

Shortly after you have returned to home key, the shutter will open again, and the cycle will be repeated.

---Each color will be presented the same number of times.

---The order of occurrence of the colors will be random. Thus it is possible for the same color to appear two or more times in a row.

White noise will be presented throughout the experiment to prevent equipment sounds and other extraneous noises from distracting you.

And now to explain the scoring procedure. First of all, the 'best' score is the lowest score, and the score is composed of three components added together. The first component is your average control activation time, that is, the average time from the opening of the shutter until you make a keypress. The second component is a penalty for errors, specifically, the addition of 1/10th of your average control activation time for each error. The final component is 1/2 of your average time off home key.

To repeat, remembering that the lowest score is best, your score is the sum of your average control activation time, plus an additional 1/10th of this control activation time for each error, plus 1/2 of the average time you are off home key on each trial.

Therefore, in order to achieve the best score, you should: (1) respond accurately. Ten errors add to your score a component as large as your control activation time. Remember also that making more than one keypress on a trial always counts as a double error even if one of the keypresses is correct; and (2) remain on home key until you are relatively certain which keypress to make. Move rapidly to make it. Then return as fast as you can to home key. This procedure minimizes both control activation time and the total time you are off home key.

Finally, the instructions have been presented in this way so that every subject receives identically the same instructions. All of the information necessary to perform the experiment is given here, so please do not ask additional questions at this time. Any questions you may have about the nature of the experiment will be gladly answered at the end of the experiment, so please wait until then.

You may now take a few moments to look over the printed instructions. You may also make some practice keypresses to get the 'feel' of the equipment if you so desire.

Note that the experiment will last approximately 50 minutes with a rest break at about the midway point.

APPENDIX 5

TEXT OF THE RECORDED AND PRINTED INSTRUCTIONS EMPLOYED WITH ENSEMBLE F(8)

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TEXT OF THE RECORDED AND PRINTED INSTRUCTIONS EMPLOYED WITH ENSEMBLE F(8)

This is a human factors experiment designed to learn something about the nature of human performance that can be expected with different types of control devices. You will only use one type of control. Later the performance of all the subjects using this same control will be compared with the performance of groups using other controls.

You will receive grade credit in your psychology class for cooperative participation in this experiment, irrespective of your performance. However, for interest and incentive, a $5.00 prize will be given to the subject using each type of control who earns the best score. The way you are scored will be explained as soon as the task is described.

The task is a simple one, but the object is to respond as fast as you can without making mistakes. First, sit comfortably at the booth. Put your preferred hand on the home key just behind the lip and hold it down firmly. Put your other hand in your lap. You will use only your preferred hand throughout this experiment. Now look at the black shutter in front of you. When the shutter opens, a color sample will be seen which is the same as one of the colors on the plate just under the shutter. The placement of the colors on the plate indicates which key should be selected and in which direction it should be pressed--either up, down, right, or left. As soon as you have decided which keypress to make, leave home key, make the chosen keypress, and then return as fast as you can to home key. Do not make more than one keypress on a trial, even if you make an error. Making more than one keypress will count as a double error, even if one is correct.

Shortly after you have returned to home key, the shutter will open again and the cycle will be repeated.

---Each color will be presented the same number of times.

---The order of occurrence of the colors will be random. Thus it is possible for the same color to appear two or more times in a row.

White noise will be presented throughout the experiment to prevent equipment sounds and other extraneous noises from distracting you.

And now to explain the scoring procedure. First of all, the 'best' score is the lowest score, and the score is composed of three components added together. The first component is your average control activation time, that is, the average time from the opening of the shutter until you make a keypress. The second component is a penalty for errors, specifically, the addition of 1/10th of your average control activation time for each error. The final component is 1/2 of your average time off home key.

To repeat, remembering that the lowest score is best, your score is the sum of your average control activation time, plus an additional 1/10th of this control activation time for each error, plus 1/2 of the average time you are off home key on each trial.

Therefore, in order to achieve the best score, you should: (1) respond accurately. Ten errors add to your score a component as large as your control activation time. Remember also that making more than one keypress on a trial always counts as a double error even if one of the keypresses is correct; and (2) remain on home key until you are relatively certain which keypress to make. Move rapidly to make it. Then return as fast as you can to home key. This procedure minimizes both control activation time and the total time you are off home key.

Finally, the instructions have been presented in this way so that every subject receives identically the same instructions. All the information necessary to perform the experiment is given here, so please do not ask additional questions at this time. Any questions you may have about the nature of the experiment will be gladly answered at the end of the experiment, so please wait until then.

You may now take a few moments to look over the printed instructions. You may also make some practice keypresses to get the 'feel' of the equipment if you so desire.

Note that the experiment will last approximately 50 minutes with a rest break at about the midway point.

APPENDIX 6

GROUP MEAN CAT PER 24 TRIAL BLOCK IN SECONDS

APPENDIX 6

GROUP MEAN CAT PER 24 TRIAL BLOCK IN SECONDS

Block (Trials)	S(4)	S(8)	F(4)	F(8)
1 (1-24)	.801	1.216	.809	1.087
2 (25-48)	.711	1.111	.795	1.021
3 (49-72)	.677	1.046	.780	1.011
4 (73-96)	.662	1.029	.777	.999
5 (97-120)	.672	.999	.759	.990
6 (121-144)	.675	.997	.767	.975
7 (145-168)	.673	.968	.748	.949
8 (169-192)	.688	.966	.759	.947

APPENDIX 7

ANALYSIS OF THE SYMMETRY OF EACH SUBJECT'S CAT DISTRIBUTION FOR TRIALS 49-168

APPENDIX 7

ANALYSIS OF THE SYMMETRY OF EACH SUBJECT'S CAT DISTRIBUTION FOR TRIALS 49-168

Ensemble	Subject	Skewness	Probability[1]
S(8)	1	11.1163	.0000
	2	4.4312	.0001
	3	4.3276	.0001
	4	4.1885	.0001
	5	3.3566	.0012
	6	6.4034	.0000
	7	3.4376	.0010
	8	5.4982	.0000
	9	5.3804	.0000
	10	7.7138	.0000
	11	14.2327	.0000
	12	9.2401	.0000
S(4)	21	14.7351	.0000
	22	8.4529	.0000
	23	6.1544	.0000
	24	- .1401	.8836
	25	3.8187	.0004
	26	13.1842	.0000
	27	.3846	.7027
	28	2.1571	.0293
	29	1.4202	.1520
	30	9.8483	.0000
	31	8.5907	.0000
	32	3.3871	.0011

APPENDIX 7 (continued)

F(8)	41	3.3280	.0013
	42	5.4354	.0000
	43	13.4581	.0000
	44	6.5646	.0000
	45	6.1624	.0000
	46	10.6103	.0000
	47	1.4316	.1487
	48	10.4357	.0000
	49	5.7075	.0000
	50	4.2145	.0001
	51	3.8620	.0003
	52	5.7264	.0000
F(4)	61	8.6693	.0000
	62	8.9226	.0000
	63	3.8303	.0003
	64	4.4768	.0001
	65	7.0471	.0000
	66	5.0339	.0000
	67	1.8014	.0683
	68	2.2346	.0241
	69	3.3055	.0014
	70	3.7873	.0004
	71	.9713	.6670
	72	5.4992	.0000

[1]The probability that the sample of CAT scores came from a population which was symmetrically distributed about the mean, i.e., that had skewness = 0.

APPENDIX 8

SUMMARY OF INDIVIDUAL DATA FOR TRIALS 49-168

APPENDIX 8

SUMMARY OF INDIVIDUAL DATA FOR TRIALS 49-168

Sub-ject	CAT (in secs.) mean	CAT (in secs.) median	Latency (in secs.) mean	Latency (in secs.) median	MT (in secs.) mean	MT (in secs.) median	ITR (in bits/sec.)	Latency-CAT Correlation	Errors
1.	1.052	1.013	.783	.746	.268	.222	2.952	.7626	0
2.	1.092	1.045	.882	.852	.210	.172	2.863	.8579	1
3.	1.066	.987	.890	.804	.176	.163	3.009	.9842	0
4.	.885	.862	.587	.585	.297	.256	3.342	.4156	4
5.	.844	.810	.602	.585	.242	.206	3.493	.7794	6
6.	1.151	1.059	.902	.819	.249	.225	2.678	.9398	2
7.	.918	.903	.619	.614	.299	.290	3.327	.8549	0
8.	1.034	.943	.843	.769	.191	.182	3.087	.9447	2
9.	1.022	.957	.833	.747	.189	.155	3.131	.8569	2
10.	1.168	1.118	.877	.864	.290	.208	2.754	.6693	0
11.	.795	.766	.602	.589	.193	.170	3.709	.5791	5
12.	1.068	.985	.718	.674	.350	.287	2.963	.5655	0
21.	.730	.701	.549	.548	.181	.133	2.850	.1560	0
22.	.669	.669	.447	.450	.241	.193	3.032	.3333	1
23.	.652	.637	.378	.383	.274	.255	3.073	.2042	2
24.	.688	.684	.426	.434	.262	.227	3.007	.5109	1
25.	.563	.536	.298	.287	.265	.241	3.608	.3410	3
26.	.697	.667	.396	.377	.300	.260	2.992	.3989	0
27.	.758	.759	.425	.430	.332	.321	2.687	.5821	0
28.	.659	.643	.428	.430	.231	.207	3.130	.6730	1
29.	.699	.694	.405	.397	.294	.297	2.917	.3988	0
30.	.689	.689	.474	.474	.215	.202	3.001	.9380	1
31.	.613	.600	.394	.392	.219	.202	3.280	.4387	1
32.	.6239	.617	.346	.343	.278	.270	3.237	.4287	1

APPENDIX 8 (continued)

Sub-ject	CAT (in secs.) mean	CAT (in secs.) median	Latency (in secs.) mean	Latency (in secs.) median	MT (in secs.) mean	MT (in secs.) median	ITR (in bits/sec.)	Latency-CAT Correlation	Errors
41.	.959	.945	.435	.425	.524	.509	3.193	.3492	0
42.	.851	.842	.412	.403	.439	.419	3.565	.3894	0
43.	.895	.854	.420	.415	.475	.415	3.543	.0950	0
44.	.998	.946	.500	.495	.498	.459	3.140	.2051	0
45.	.951	.899	.482	.484	.468	.389	3.339	.0288	0
46.	1.094	1.061	.781	.781	.313	.283	2.804	.7061	1
47.	1.116	1.077	.633	.620	.483	.438	2.733	.3413	1
48.	1.018	.991	.541	.546	.476	.435	2.991	.0356	1
49.	.988	.947	.565	.575	.423	.325	3.192	.4059	1
50.	.844	.830	.562	.569	.282	.249	3.591	.6975	2
51.	1.130	1.100	.719	.708	.411	.375	2.670	.6872	2
52.	.973	.957	.671	.678	.302	.246	3.118	.6417	4
61.	.870	.844	.442	.444	.428	.389	2.353	.2155	0
62.	.818	.815	.389	.390	.429	.419	2.485	.1253	1
63.	.828	.820	.361	.358	.467	.445	2.408	.2943	2
64.	.707	.687	.355	.352	.353	.323	2.893	.4301	1
65.	.617	.602	.349	.347	.268	.247	3.187	.4737	4
66.	.728	.702	.445	.449	.283	.237	2.723	.4914	5
67.	.758	.758	.518	.520	.241	.230	2.691	.7855	0
68.	.858	.845	.337	.336	.521	.505	2.385	.3516	0
69.	.801	.787	.367	.362	.434	.422	2.519	.1968	1
70.	.749	.742	.382	.374	.367	.349	2.677	.3729	1
71.	.690	.690	.442	.448	.248	.219	2.921	.5979	1
72.	.767	.726	.420	.424	.347	.305	2.613	.3647	3

APPENDIX 9

STIMULUS SUBSET GROUP MEANS

APPENDIX 9

STIMULUS SUBSET GROUP MEANS

	S(4)A	S(4)D	F(4)A	F(4)D
Mean CAT (in seconds)	.6515	.6920	.7707	.7617
Median CAT (in seconds)	.6405	.6755	.7580	.7450
ITR (in bits/second)	3.1337	3.0020	2.6343	2.6748
Number of Errors	1.1667	.6667	1.0000	2.1667

APPENDIX 10

STIMULUS SUBSET (COLOR EFFECT) ANALYSES: RESULTS OF ANALYSES OF VARIANCE INDEPENDENTLY PERFORMED ON MEAN CAT, MEDIAN CAT, ITR, AND ERROR DATA

APPENDIX 10

STIMULUS SUBSET (COLOR EFFECT) ANALYSES: RESULTS OF ANALYSES OF VARIANCE INDEPENDENTLY PERFORMED ON MEAN CAT, MEDIAN CAT, ITR, AND ERROR DATA

Source	Dependent Variable	F
Switch Type	CAT (mean)	12.3967**
	CAT (median)	11.3527**
	ITR	16.6082***
	Errors	1.6162
Stimulus Subset	CAT (mean)	.3460
	CAT (median)	.1572
	ITR	.2021
	Errors	.4040
Interaction	CAT (mean)	.8546
	CAT (median)	.7480
	ITR	.7206
	Errors	2.5253

*$p < .05$.
**$p < .01$.
***$p < .001$

Note.--For each F, $df = 1, 20$.

APPENDIX 11

RESULTS OF DISTRIBUTION ANALYSES PERFORMED ON THE INTRASUBJECT LATENCY-CAT CORRELATIONS FOR EACH GROUP

APPENDIX 11

RESULTS OF DISTRIBUTION ANALYSES PERFORMED ON THE INTRASUBJECT LATENCY-CAT CORRELATIONS FOR EACH GROUP

Group	Skewness	P[1]	Kurtosis	P[1]
S(4)	1.2385	.2132	.4119	.6838
S(8)	- .8941	.6250	-.4788	.6378
F(4)	.8497	.5997	.0183	.9830
F(8)	- .0259	.9776	-.9669	.6647

[1] P is the probability that the sample distribution came from a population of intercorrelations having a normal distribution, i.e., skewness = 0 and kurtosis = 0.

APPENDIX 12

MEAN MT FOR ALL OCCURRENCES (TRIALS 49-168) OF PHYSICALLY EQUIVALENT KEYPRESSES

APPENDIX 12

MEAN MT FOR ALL OCCURRENCES (TRIALS 49-168) OF PHYSICALLY EQUIVALENT KEYPRESSES

Group	Subject	Mean MT (in seconds)	Group	Subject	Mean MT (in seconds)
S(8)	01	.2574	F(8)	41	.4998
	02	.1718		42	.4575
	03	.1712		43	.4963
	04	.2435		44	.5640
	05	.2226		45	.3916
	06	.2235		46	.2861
	07	.3086		47	.4318
	08	.2125		48	.4832
	09	.1688		49	.3861
	10	.3911		50	.2888
	11	.1961		51	.3882
	12	.3591		52	.3084
S(4)	21	.1902	F(4)	61	.3999
	22	.2527		62	.4912
	23	.3075		63	.4368
	24	.2830		64	.3256
	25	.2260		65	.2703
	26	.2585		66	.2833
	27	.3418		67	.2201
	28	.2185		68	.4928
	29	.2761		69	.4254
	30	.2259		70	.3234
	31	.2206		71	.2914
	32	.2691		72	.4727

APPENDIX 13

ANALYSIS OF VARIANCE OF MEAN MT FOR PHYSICALLY EQUIVALENT KEYPRESSES

APPENDIX 13

ANALYSIS OF VARIANCE OF MEAN MT FOR PHYSICALLY EQUIVALENT KEYPRESSES

Source	*df*	*F*
Switch Type	1,44	40.0580***
Number of Alternatives	1,44	.5628
Interaction	1,44	1.6442

*$p < .05$.
**$p < .01$.
***$p < .001$.

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