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Final Report

Human Performance Capabilities

Eugene Galanter

1 October 1976

Contract N00014-67-A-0108-0031

NR 197-016

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This is the final report for Contract No. N00014-67-A-0108-0031, Work Unit 197-016 that reviews the research, both experimental and theoretical, conducted by the Psychophysics Laboratory, Columbia University, from 1 October 1971 through 31 December 1975. Three main sections discuss 1) the measurement of utility, 2) response organization, and 3) Psychophysical scaling.

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Human Performance Capabilities

Final Report

Contract N00014-67-A-0108-0031

NR 197-016

Eugene Galanter

Columbia University

Introduction

Research in the Psychophysics Laboratory, Columbia University from 1 October 1971 through 31 December 1975 has concentrated on three interconnected problems.

A. The measurement of the incremental utility of monetary and non-monetary outcomes both positive and negative.

B. The experimental study of response organization by the use of a reaction time paradigm, and in particular the development of sequential response experiments; along with a new conceptual theory of response organization.

C. Psychophysical scaling of dynamic perceptual events under field conditions, and the integration of these psychophysical scales into the perceptual-motor performance theory mentioned in B. above.

In the research summary that follows we treat each of these areas as a separable entity. The reader should recognize that as products of a single laboratory the research reported here represents an interlocking program of associated problems. The various graduate students and scientists who participated in this work developed a common vocabulary to discuss these experiments in terms that made them intercomparable. Here, we shall chuck this laboratory jargon, and present our findings within the classical psychological conventions.

The Measurement of Utility

Since the publication of The Direct Measurement of Utility and Subjective Probability (Galanter, 1962) we have been concerned with the psychic representation of monetary value. Insofar as money is the culturally pervasive objective scale of the value of human performance, the measurement of its psychic effects is tantamount to a (one-dimensional) theory of human motivation. Such measurement has deviled experimentalists since the turn of the century. For an historically oriented discussion of this background, see Galanter (1974).

The measurement of the utility of money by direct magnitude estimation methods was initially accomplished by the subterfuge of asking subjects to judge something about their subjective happiness as a consequence of various monetary gains and losses. The results of these and many other similar experiments converged on a power function as the utility function for money. The incremental utility for money increased at approximately the square root of the monetary increments, and the disutility of monetary losses decreased at about the same rate. Refinements in the experimentation by Galanter & Pliner (1974) suggested that the rate of utility gain for monetary increments is slightly slower than the rate of utility loss for monetary decrements.

This second order finding is of some interest insofar as it may be related to the dynamic mechanisms of incremental utility. Thus, although it would be ideal to have an algebra of utility that enabled us to calculate the final utility of increments of X dollars minus decrements of Y dollars, currently we must settle for a utility estimate of the consequences of the total transaction. In the context of our current understanding we consider these dynamic phenomena as a static event that represents either an increment or a decrement in monetary value, and has a single utility associated with it. Under the subject contract pilot experiments were performed to try to assess dynamic utility. The experimental paradigm (a social psychological experiment) required that two groups of subjects appear to participate in an experimental auction. One group received \$2 with which to participate in the auction. The other group received \$5, and then because of a "mistake" by the assistant had to refund \$3 before the experimental auction began. The true experimental question concerned the utility of the \$2 held by each group. Although questionnaire data supported the conjecture that the utility of \$2 arrived at by \$5 minus \$3 was less than the utility of \$2 directly received, the subsequent experimental attempts to assess these differences behaviorally did not yield data that were statistically significant. If new experimental procedures could be developed to examine this problem, it could lead to a utility equation that would permit calculation not only of monetary increments and decrements, but of combinations of such gains and losses with other valuable or noisome commodity bundles.

Be that as it may, the continuing refinement of utility scaling left us in a position of arguing on the basis of scaling experiments that the growth and decline of subjective value--utility--followed a power law with an intuitively plausible exponent. The next step was to ask whether this utility function predicted the ongoing behavior of people guided by the consequences of their actions. To study this problem we turned to experiments within the context of the theory of signal detectability. In this paradigm, subjects are asked to make decisions about limenal events, and they receive feedback in the form of rewards and losses contingent on their decisions and the payoffs posted by the experimenters. In the normal form of the experiment, subjects gain and lose small quantities of money on each of a sequence of trials in which they correctly or incorrectly detect, discriminate, or identify the presence, absence, or difference among various stimulus events presented to them. The experimental question at issue is whether by characterizing the entries in the payoff matrix of such an experiment as utilities calculated from previously ascertained utility functions, we would be able to predict the performance of the subjects in these experiments simply from a knowledge of the entries in the payoff matrix. After various attempts at experiments to assess this predictive power of the utility function, we can state with some confidence that the utility function that we have observed by the methods of magnitude estimation which yield exponents of ca. 0.45 for increments and, ca. 0.55 for decrements are sufficient to predict the reinforcing effects of trial-by-trial payoffs in a signal detection type of experimental paradigm. This result, reported by Kornbrot and Galanter (JEP in press) is shown in Table 1. These data justify the interpretation of the utility scale obtained by direct methods as a metric with predictive power for behavioral experiments. The data of Table 1 were analyzed to estimate the utility function parameter for the assumed power function based on the hypothesis that either the theory of signal detectability, or the choice theory of threshold determination was the appropriate model of the sensory effects. Although the estimates of the slope function differ significantly ($p < .01$) depending on the sensory theory that is used, neither of the estimates of the slopes differ over all from the estimates of the parameter based on psychophysical scaling data. The table also shows that averaging across subjects by blocks as compared to averaging within subjects across blocks makes neither a practical nor a statistical difference in the observed values.

Success in the scaling of money led us to the question of whether utility theory, that is a theory that ascribes all of human value to a one-dimensional continuum, is adequate to cope with the plurality of events that are either desired or despised by people. Consequently we extended the magnitude estimation experiments on the utility of money to encompass the utility of events that were not directly monetary in nature. Thus for example, we wanted to estimate the numerical utility of "successfully completing your income tax return, " or the disutility of "getting a flat tire on your way to work." It was simple to get people to assign magnitude estimation values to the utilities and disutilities of a variety of events of this kind. However, there was no intrinsic evidence in these data to support the view that such a derived utility value for events represented anything more meaningful than the accidental numbering behavior that people happened to adopt. In order to "validate" in some sense the observed utilities assigned to these non-monetary events, subjects were asked to judge the utility of monetary events in the context of these non-monetary events.

Interspersed among the requests for utility estimates for non-monetary events were additional queries for estimates that included items such as "you have won the state lottery for $5,000," or "you have lost a civil suit for $1,600." With a half dozen of these monetary items intercollated among the non-monetary ones, we were then able in the subsequent data analysis to extract the monetary events and plot them against money. This permitted us to ascertain if the utility function for the monetary events embedded in the non-monetary items yielded the same exponent as the utility function for monetary events estimated alone. The results of our initial experiments (PLR-36) lends support to that hypothesis (see Figure 1).

The consequence of this class of experiments is that we are now able

Table 1

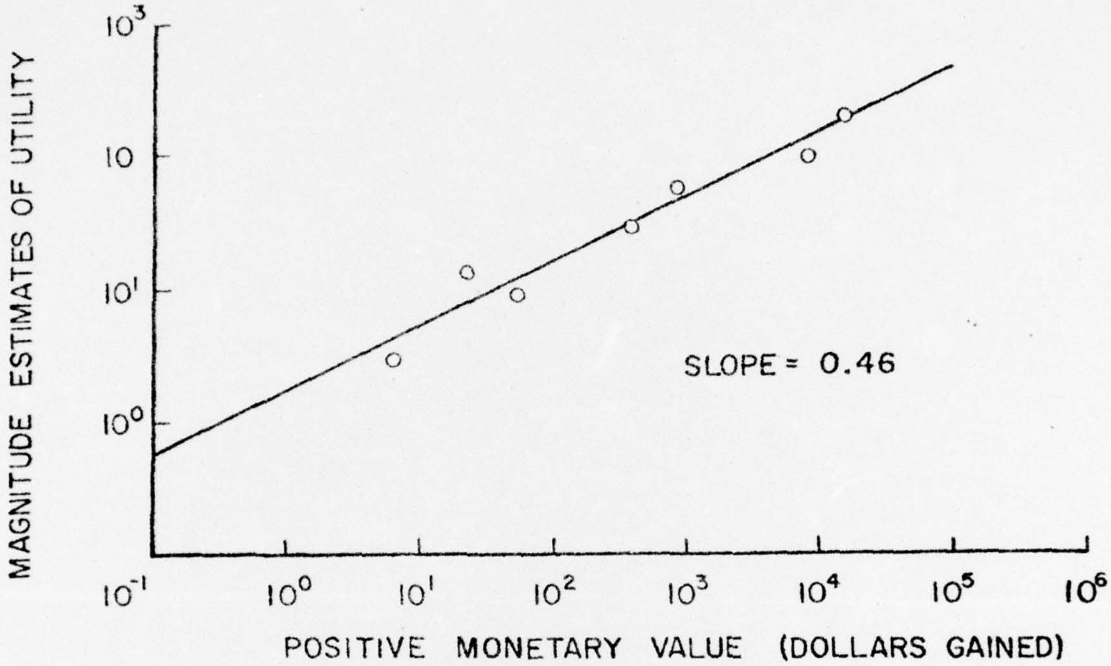
Values of the utility function exponent estimated from psychophysical experiments. Two different theories were used to characterize the perceptual responses.

Signal Detection Theory Analysis

	All Pay-Offs Positive Estimated utility function exponent for increments of money.	All Pay-Offs Negative Estimated utility function exponent for decrements of money.
Averaged by S's	0.59	0.60
Averaged by Blocks	0.60	0.59

Choice Theory Analysis

	All Pay-Offs Positive Estimated utility function exponent for increments of money.	All Pay-Offs Negative Estimated utility function exponent for decrements of money.
Averaged by S's	0.37	0.39
Averaged by Blocks	0.39	0.37


10³
10
10¹
10⁰
MAGNITUDE ESTIMATES OF UTILITY
SLOPE = 0.46
10⁻¹
10⁰
10¹
10²
10³
10⁴
10⁵
10⁶
POSITIVE MONETARY VALUE (DOLLARS GAINED)

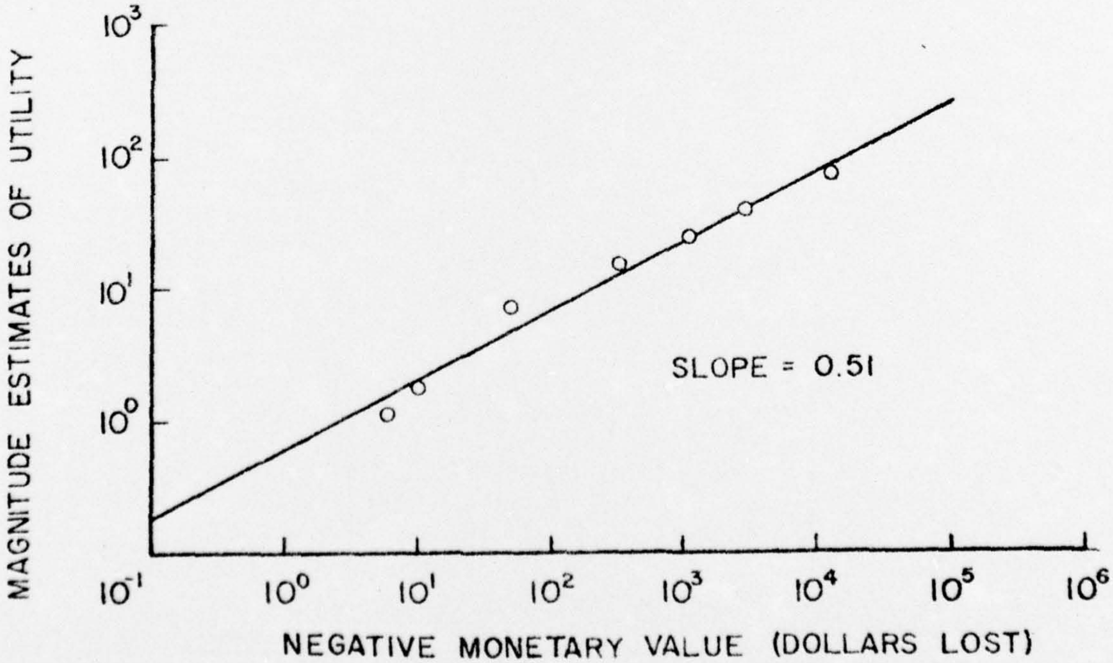

10³
10²
10¹
10⁰
MAGNITUDE ESTIMATES OF UTILITY
SLOPE = 0.51
10⁻¹
10⁰
10¹
10²
10³
10⁴
10⁵
10⁶
NEGATIVE MONETARY VALUE (DOLLARS LOST)

FIG. 1

to measure (in the empirical sense of that term) the relative values associated with a variety of events by individuals. Insofar as the goal of the scientific enterprise is more than simply the titillation of the scientific imagination, then a ramification of these experiments is to make the measurement of human values amenable to the same kinds of practical goals as the empirical analysis of human intellectual performance, or the assessment of personality by psychometric techniques. We here propose the use of these utility measurement techniques for the practical assessment of incentive systems, environmental annoyance, public safety procedures, and in general for the evaluation of the consequential effects of policy decisions.

It should be remarked in closing this section that there are many theoretical issues involved in the measurement of utility from the mathematical side that are only tangentially touched by our work. The development of coherent mathematical models for utility scaling using the classical criteria of such models has not been attempted except for a small sortie by Jacobs (1973) who hoped to find a technique for converging the obtained utility scale from magnitude estimation experiments with category scales of utility that could be subsumed under a Thurstonian model. We have not pursued the development of such mathematical models simply because it seemed prudent to grasp first the broad outlines of the nature of human utility judgments, and the plausibility of the utility idea as a general conception of human motivation before developing models that could constrain our experimentation.

In the course of these researches we have been led from time to time to conjecture alternatives to the one-dimensional model of motivation that utility theory proposes. However without a richer theory to guide us, we have been unable to capture the intuitively plausible view that there are other things in the world beside money or its utility transform, that counts. In the next section we discuss a theory of action that may accommodate some of these ideas.

Response Organization

Most psychologists presume that once perceptual information has been appropriately encoded and evaluated and the costs and benefits of alternative courses of action assessed, behavior is instituted that optimizes the functional relations between the perceptual environment and the conjectured outcomes. In the section that follows we will talk about the scaling of perceptual phenomena and their relation to action, here we will concentrate on the question of whether, given appropriate perceptual information and its correlation with outcomes whose utilities can be assessed, behavior can be construed as action guided by continuous or possibly intermittent feedback of perceptual information about the action, or changes in the utility states of the individual.

As outlined above such a conceptualization of human action, guided by perceptual information on the one hand and the consequential outcomes of action on the other, represents a central tenet of modern behavior theory. It is exemplified in work as disparate in its spirit as that of B. F. Skinner and the general principles of operant conditioning (cf.

Skinner, 1938) to the cognitive theory of Plans and the Structure of Behavior, as proposed by Miller, Galanter, and Pribram (1960).

Experimental work conducted under a previous contract with the Office of Naval Research had given us an opportunity to engage in perceptual scaling during the performance of dynamic tasks--manuevering an aircraft and obtaining judgments about visual and temporal perceptions of environments external to the aircraft. In the course of this work it appeared that much of the over-all guidance was accomplished without any reliance whatsoever on either visual sensory information from outside the aircraft, or informational data from the instrument display in the aircraft itself. Informal experiments indicated that an on-time duty cycle of ten percent in the visual system was sufficient to provide adequate information for the guidance of a light aircraft through a standard approach and landing pattern down to within three seconds of the tóuchdown point.

These results led us to believe that enormous segments of the behavior associated with the primary task of landing the aircraft were not under local stimulus control, but rather were run off as an essentially ballistic act. Clearly, during the course of such a ballistic act other maneuvers were instituted that were under local feedback control. These included, for example, maintaining a "wings level" attitude of the aircraft during the final approach phase. However it was obvious, at the intuitive level, that maintaining a "wings level" attitude was not part of the landing procedure, rather it was a housekeeping chore performed through the operation of feedback information that served the primary ballistic task of getting the airplane down. As a result of these informal observations and experiments, we concluded that the classical theory of psychological behavior, based as it is upon the general principles of feedback correction of ongoing actions, might itself be modulated through some new feedback. This feedback theory had become so well entrenched as to carry psychological experimentalists along by its own ballistic dynamics. Consequently members of the laboratory and other colleagues consorted in the discussion and development of an alternative to the generally accepted principle of feedback guidance and behavioral control to develop an alternative conceptual schema. This new approach although not necessarily contradictory to existing theory, represents at least a supplemental set of ideas with some potential for new and altered understanding.

The central point of this modification of "adjustive" psychological theory is that the primary structure of action is ballistic. This is not merely to say that there are certain small acts that are known to be ballistic, e.g., eye movements, but rather that behavior in the large is often ballistic in its structure, not under the control of on-line perceptual information. In a sense, we are abandoning what we have called the doctrine of "local advancement." In S-R theory this usually takes the form of the chaining of S-R responses in which some item further down the chain is irrelevant to the current action. In cognituve theory it takes the form of a tactical organization of plans so that subsequent action sequences are conditional upon the outcome of certain test operations.

To characterize the nature of ballistic action in the context of the present discussion we construe two criteria as being central to the theory, and also capable of potential behavioral observation. These criteria are:

1) that behavior may continue for some time beyone a "stop command" delivered by the present perceptual information, and

2) that the return to on-course behavior following a deviation from the intended course of action is quantal i.e., not a return graded to the magnitude of the deviation.

Thus, a "ballistic act" is a preprogrammed enduring course of action defined by the intentions of the actor in terms of scaler utilities consequential to the consummation of the intention.

Our original conception of human action as planned and foresightful relied primarily upon a continuing servo-system modulation. That model made many assumptions about the continuous goal directed guidance or feedback that was contained in the overall structure of task-oriented performance. The current proposal involves the notion that the intentional acts are primarily ballistic, and the servo-like modulations of the course of action that accompany the action are intended primarily either to keep the final goal accessable to some perceptual monitoring system or to reevaluate the utility of the goal. Another way to think of this revision of our original theory, is that people act as though their ballistic target requires them to transverse a viscous and turbulent medium whose perturbations influence their actions. These transient perturbations are accommodated by local feedback controlled adjustments much in the way that an inertial guidance system functions in a ballistic vehicle to ensure continuous on-course progress in the face of local turbulance.

The notion that sub-plans function to accommodate a final goal is what we here eschew, as do the S-R theorists. Local acts serve only local purposes. Of central importance to this theory is the premise that the time scale of a behavior is the major correlate of the underlying mechanism of the behavior. In some cases, this premise is simply a restatement of experimental findings. In other contexts it results in a recasting of the proposed mechanisms of behavior in the large. The current literature inverts the view we here propose. Generally, experimental data are presented to support the position that ballistic or pre-programmed action sequences occur in the small (Klapp, 1975) or the fast (Roy and Martenuik, 1974), and that larger, or slower behavior patterns conform to the closed-loop, or feedback hypothesis (Adams, Goetz, and Marshall, 1972). This is probably true, and our own experiments on fast reaction times (Galanter, Brief, and Owens, 1971) add to this data base. But what we here mean by slow and large behavior is several orders of magnitude slower and larger than the current literature examines. Here we mean what has been called classically "molar" behavior. In the real world such behavior is defined by its "intentionality," e.g., "landing an airplane." Classical theory has always attempted to breakdown such molar acts into molecular segments. The resynthesis of these segments constitutes the classical aim of behavior theory. The feedback hypothesis is one such mechanism for linking these molecular acts, even where these acts are larger than the twitch-like components of of which they may be composed.

Implicitly, however, it is assumed that if the feedback hypothesis is true for "big" pieces of behavior, it is certainly true for "bigger" pieces. What we here propose is that to the contrary, it is the very small and fast, and the very large and elaborate behaviors that are ballistic, whereas the mid-sized but still really quite small behavior patterns are servo-controlled. But before we plunge ahead with a discussion of large scale ballistic acts, let us review the feedback hypothesis once again and examine some criticisms of it as an explanatory concept for behavior in the large.

The feedback, or closed loop hypothesis of motor control is the most widely accepted structure in contemporary psycho-motor theorizing. (Garvey and Mitnik, 1957; Anokhin, 1969; Chase, 1965; Weiss, 1950). It has been used as an underpinning for tasks as diverse as the transformation of the punctate action of neural elements into behaviorally meaningful conglomerates, while it has also served as a metaphorical description of the organization of complex temporally extensive molar behavior. The central question which we raise however, concerns the heuristic and substantive value of continued use of the feedback hypothesis alone, in the molar analysis of complex motor acts.

There are at least three considerations which argue that one must be careful about the scope of feedback modification in human action:

1) the temporal characteristics of action, in the small (and in the large) may be too small to allow efficient integration of the information potentially available for feedback,

2) a priori, the existence of response-mediated feedback is not a sufficient condition for the uniqueness of a feedback mechanism of movement control. The functional importance of feedback must be empirically validated, particularly in contexts which vary the relative value in the behavioral economy of servo-damped accuracy.

3) the formal description of a feedback loop suggests a typology of human sensory capacities and perceptual styles which are at variance with our present conception of the large scale psychophysics of human perception. In particular, the linearity of the error operator runs counter to many of the results of psychophysical scaling experiments.

It has long been known that some sequential movements are executed so quickly that it is difficult to understand how feedback could be utilized in their execution. This point was first detailed by Lashley (1951) and subsequent measures of reaction times to both visual (Keele and Posner, 1968) and kinesthetic feedback (Chernikoff and Taylor, 1952) strongly suggest that many small scale movements must occur in the absence of feedback.

In this laboratory, experiments on serial inter-response times (Galanter, Brief, and Owens, 1971) show mean inter-response times as low as 12 msec., suggesting a rate of roughly 80 responses/second (see Figure 2). Such results are inconsistent with S-R chaining models in general and the feedback hypothesis in particular. Furthermore, centroid analysis of motor skills by Fleishman (1954) has shown that these serial responses are one of the two principal factors in complex motor skills. The other major factor loading he reported was fine positional movements, which occurred only during the very late stages of the action and were, presumably, feedback controlled. This late-stage grading is probably the result of the very steep reward gradients which appear during the final stages of skilled acts such as behavior in the touchdown zone during the landing of an airplane. This is properly the province of the second criticism and will be returned to subsequently. McLaughlin (1967) demonstrated that entire bi-phasic eye-movement (Woodworth, 1899) responses can be completed in less time than would be required for feedback to serve effectively. In particular he showed that when the target is moved upon response initiation, that the response is appropriate for the initial target with delayed correction. Festinger and Canon (1965) have also demonstrated this effect using eye movements as the response.

Gibbs (1970) presents data suggesting the ballistic nature of corrective actions. In plots of position versus time, corrections occur as piecewise-continuous segments rather than as curvilinear returns to track as expected under servo-damping. Poulton (1957) demonstrated that target rather than cursor intermittencies are most damaging to tracking behavior. This can also be explained as a result of the ballistic nature of responses, because a cursor intermittency represent no real loss of information. Indeed, such intermittencies would represent no loss at all if they matched exactly the time course of the ballistic components. The usual interpretation of these experiments that assigns major value to kinesthetic feedback in this context is questionable insofar as the delay times in neural transmission have been shown to be too long to support such a mechanism (Chernikoff and Taylor, 1952).

There is no reason to expect that the situation is much different as we move to behavior with a longer time scale for the following reasons. The local short-term components are of little or no immediate value, as evidenced above. As the complexity of the action, in toto, increases the information available is generally degraded. That is, large-scale actions generally possess a time course large enough to make the average information per unit time decrease. This is because the coding schemes used to make the information structure of a complex act possible place limits on the rate of growth of information (in bits) as a function of task complexity (Miller, 1956). Thus as the time of the action grows longer the information context--the average rate of information--decreases and the temporal interval between informative points increases. This is an example of the time scale premise alluded to earlier. The result is that it is reasonable to suppose that it would be biologically advantageous, in many contexts, to pre-plan the course of extensive actions. That is, it may be the case that ballistic action is more efficient than servo-damped control from the viewpoint of the organism. No reasonable data on this question seems to be available.

The second point, that feedback may have little functional value, must be considered carefully in any interpretation of the data on human performance.

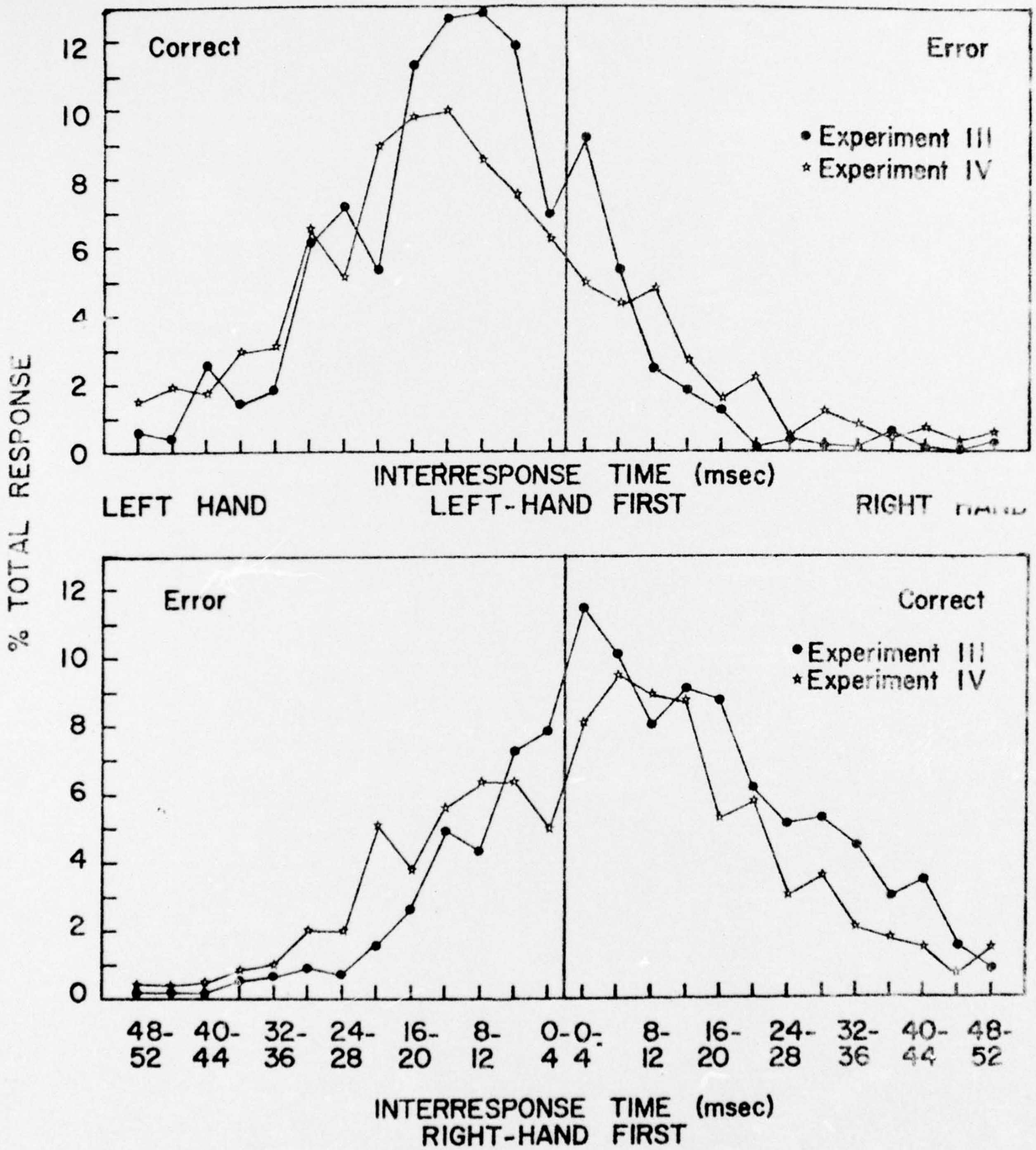

12
10
8
6
4
2
0
Correct
Error
• Experiment III
* Experiment IV
INTERRESPONSE TIME (msec)
LEFT HAND
LEFT-HAND FIRST
RIGHT
% TOTAL RESPONSE
Error
Correct
• Experiment III
* Experiment IV
48- 52
40- 44
32- 36
24- 28
16- 20
8- 12
0- 4
0- 4
8- 12
16- 20
24- 28
32- 36
40- 44
48- 52
INTERRESPONSE TIME (msec)
RIGHT-HAND FIRST

Fig. 2

Put simply, the fact is that the events consequential to an action, in the sense of pay-offs, are more important than the antecedant conditions in the formation of response probability vectors (Galanter, 1974). In particular, in contexts where the number of available choice-points (or bits/unit time of information) is relatively small, it is reasonable to propose that the total utility accruing from an action sequence could be higher under ballistic than under response-mediated control of behavior. Under such conditions, it is expected that the individual will trade servo-control for ballistic simplicity. It is certainly the case that he would choose a ballistic missile over a guided missile for, say interstellar travel if the higher pay-off accrued to the generalized enroute and terminal events of ballistic travel. Anecdotally. this country made just such a choice in defense design. The suggestion is that the same kind of choice may be evidenced in the direct behavior of individuals. Thus, although feedback control is a possible model of performance in the sense that it characterizes a way in which some hypothetical entity could accomplish its movements, there is no reason to suppose that organisms actually accomplish their actions this way.

Following Weiner (1948) most feedback theorists have assumed that the availability of feedback is tantamount to the utilization of feedback. They have pointed to evidence such as intentional tremor in cerebellar patients as proof of their hypothesis. In fact, the impressive aspect of movement pathologies is that the patients do arrive at their goals. The tremor may be understood as internally generated or autokinetic turbulence which the patient "rides through" in arriving at the goal. Presumably, increased reward gradients increase the effectiveness of this turbulence compensation. Clinically such effects are commonly referred to as "the will to live" or other such phrase. They represent the dominance of afferent cathexes in movement reactions. In the laboratory, much work concerning this problem has been done under the label of the "speed-accuracy trade-off". The central result of the speed-accuracy trade-off experiments is that appropriate arrangements of pay-off contingencies can lead at one extreme to an almost compulsive attention to detailed accuracy requiring utilization of feedback, whereas at the other extreme reactions so rapid are produced that no attention to feedback is possible as the time course of the response disallows the availability of relevant feedback information.

The effects of pay-off structures on the distributional characteristics of simple and complex reaction times were originally demonstrated by Snodgrass, Luce, and Galanter (1967). Efforts should now be made to initiate work on the deflectability of on-course behavior by off-course or incidental reward gradients. This information would serve to connect the area of the speed/accuracy of reaction time to the study of the speed/accuracy trade-off in movement time, in the context of the relations between servo-loop and ballistic performance (Schmidt, 1971; McGuigan, 1959; Pike, 1971; Luce and Green, 1972).

Before leaving this point, it is important to realize that outcomes, in the sense of pay-offs or reinforcements, are not equivalent to response mediated feed-back. For a review of the empirical distinctions see Smith (1966). In brief, pay-offs serve to delineate the task whereas feed-back serves to modulate the course of action. The point here is that the pay-off structure may so dominate the action that feed-back is of little use in the control of errors and/or deflections.

The third point of our critique of feed-back models is based on a discrepancy between the formal model of feed-back as it is normally formulated, and the empirical information on sensory capacities from which sensory scales are derived. One result of the historical development of the feed-back model is the use of linear and quasi-linear amplifiers in both the forward and the backward paths of the feed-back loop. In particular, the central tenet of servo-looping is the concept of error reduction. This error is defined as the difference between the desired or commanded output and the feed-back amplified obtained output. This is usually referred to as the "perceived" error (Ruch, 1951). Thus letting θ_i be the desired output, θ_o the actual output, and A and B the forward and the backward amplification scalers respectively, the error is defined as G, where

$$1)\quad G = \theta_i - \theta_o B = \frac{\theta_i}{1 + AB}$$

This equation demonstrates the linearity of the system gain and the effect of this gain on error reduction. However, consider the simple task of reaching for a cup of coffee. The perceived distance between cup and hand generates a signal to decrease that distance by appropriate movement of the hand towards the cup. According to the feed-back hypothesis, a series of successive damped approximations finally succeeds in bringing the hand to the cup. Even if the description is metaphorically correct, it fails to incorporate the fact that all the sensory information in this situation is represented by the psychophysical function of the physical distance. That is,

$$2)\quad \Psi(d) = ad^n$$

where d is the physical distance and a and n scale parameters (Stevens, 1961). Unless one wishes to argue that sensory scales represent events totally epiphenomenal to the business of getting around in the world, the initial command message and the continuing feed-back concerning the successively smaller remaining distances, or both must include effects due to the non-linear transduction of sensory inflow. For example, a physical error, d, between obtained and desired hand locus relative to an object gives rise to visual feed-back which most reasonably is conceived of as distance-like. Thus if d_i, d_o, d_d represent the initial, obtained and desired distances, respectively then the error, Δd, is given by:

$$3)\quad \Delta d = d_o - d_d$$

Now d_d is presumably dependent on d_i, in particular on the perceived initial distance $\Psi(d_i) = ad_i^n$. Thus

$$4)\quad d_d = F(ad_i^n)$$

In like manner the feed-forward and feed-back amplifications represent transformations on this function which may themselves be non-linear (in the sense that perceived extention is non-linear with its physical measure). Taken as a whole, the effect could be a wildly non-linear system. Of course, the role of functions, such as F may be to linearize the output. This is irrelevant for the present discussion which is solely intended to point to the possible effects that have been overlooked in the context of feed-back theory. Further experimental and analytical work is required to evaluate the appropriateness of the criticism. It is for considerations of this kind that Galanter (1974) suggested that it is important to investigate the effect of non-linear translations on human performance.

Ironically, this problem has missed the attention of many interested in motor behavior. This is probably the result of the historical fact that the physical domain most closely examined in tracking and motor behavior is physical extent, for which the psychophysical function is (nearly) linear. It is entirely possible that analogous investigations of tracking in, say, the auditory intensity domain or the tracking of visual brightness may lead to significant non-linearities in this behavior. Such nonlinearities would explain performance decrements in many real world situations such as the response to the center line strobe lights in IFR landing conditions, and the failure of the FLYBAR navigational system.

But before we consider these perceptual phenomena in detail in the next section, we turn our attention now to efforts taken in the laboratory to develop experimental paradigms for the measurement of human response time. There is no need here to delve into the long history of the reaction time experiment. Suffice it to say the experiment itself is replete with a variety of problems. One of the main problems is that the experiment seems to be transparently simple in its nature and that the control of the dependent variable--response time--often appears in experimental data to be under the control of simple characterizations of the physical stimulus. These two features of the experiment have been critized in some detail by Galanter (1966) and form the basis of the development of reaction time experiments using feed-back and pay-off principles as demonstrated by Snodgrass, Luce, and Galanter (1967).

In these studies however, the dependence of the reaction time on the physical stimulus was not examined in detail. But other classical results establish the strong dependence of the reaction time on stimulus values. Chocholle's (1945) studies of reaction time as a function of auditory intensity generated the beguiling possibility that reaction time may be represented as a simple (power function) behavioral function against physical stimuli. This psychophysical function is the most trivial representation of the stimulus parameter. However Greenbaum (1963) showed that the absolute intensity of the acoustic stimulus was not sufficient to characterize the reaction time, rather some quantity like signal-to-noise ratio was shown to be a better representation.

Following on this suggestion, we undertook a series of reaction time experiments in which the signal intensity varied by as much as two and one half orders of magnitude, whereas the signal-to-noise ratio measured in the most simple and obvious form remained constant. Results from these experiments showed that the reaction time was an invariant function of signal-to-noise ratio and that the location of the reaction distribution, i.e., the mode, was independent of the overall intensity of the input signal. (Figure 3) The variability of the distribution was also clearly dependent on the signal-to-noise ratio applied. The less the S/N the greater the variability of the reaction time; the greater the S/N the smaller the variability of the reaction time. These generalizations are true for signal-to-noise ratios measured as signal energy to noise power per unit cycle. Figure 4 shows the function relating the modal reaction time to S/N over a 70 dB dynamic range.

It should be remarked that the generation of data as consistent and reliable as shown in Figures 3 and 4 was made possible by the use of a small process-control computer to control the experimental environment. This computer, in addition to presenting the stimulus materials with appropriate randomization, also collected the response data, tallied the data, and printed out the histograms. During the development of this computer based capability, other possible sources of variation in the reaction time experiments were explored. One auxilliary study was concerned with the question of key force requirements, and its relation to the reaction time. In some contexts key force has appeared to be a variable of some interest. We had hoped that using the techniques developed for the experiment reported above we could avoid dealing with the possibility of a contaminating variable of this kind. To insure that this was the case a variable force key was designed and constructed by Bernice Rogowitz. Data were collected from three subjects with key force variations of two to three orders of magnitude. These results taken from Galanter and Owens (1973) indicated that within the experimental context we were using, and with the pay-off contingencies that were employed, the key force variable had no influence whatsoever. A typical example of these data are shown in Figure 5.

Our next intended steps in this research are to explore whether the concept of the signal-to-noise ratio serves as a general representation of the physical metric of environmental events, and consequently whether it can form the basis for a cognitive formulation of stimulus information. Our intention is to carry the experiments forward in the visual mode using light increments on background luminances. We will then measure reaction time as a function of an appropriately derived signal-to-noise ratio. Auxilliary experiments along these lines are going to be performed using light increments on configured backgrounds, having both random configurations and configurations rich in stimulus information--i.e., photographs.

A second, purely mechanical, concern but one with deep underlying physiological implications, is the study of the role of stimulus rise time. We have evolved a set of distinct models that characterize how the observer integrates information as a function of time to define the "presence of the stimulus." This temporal integration must, by its very nature, interact strongly with the reaction times that are observed. For example two of the models that we consider are:

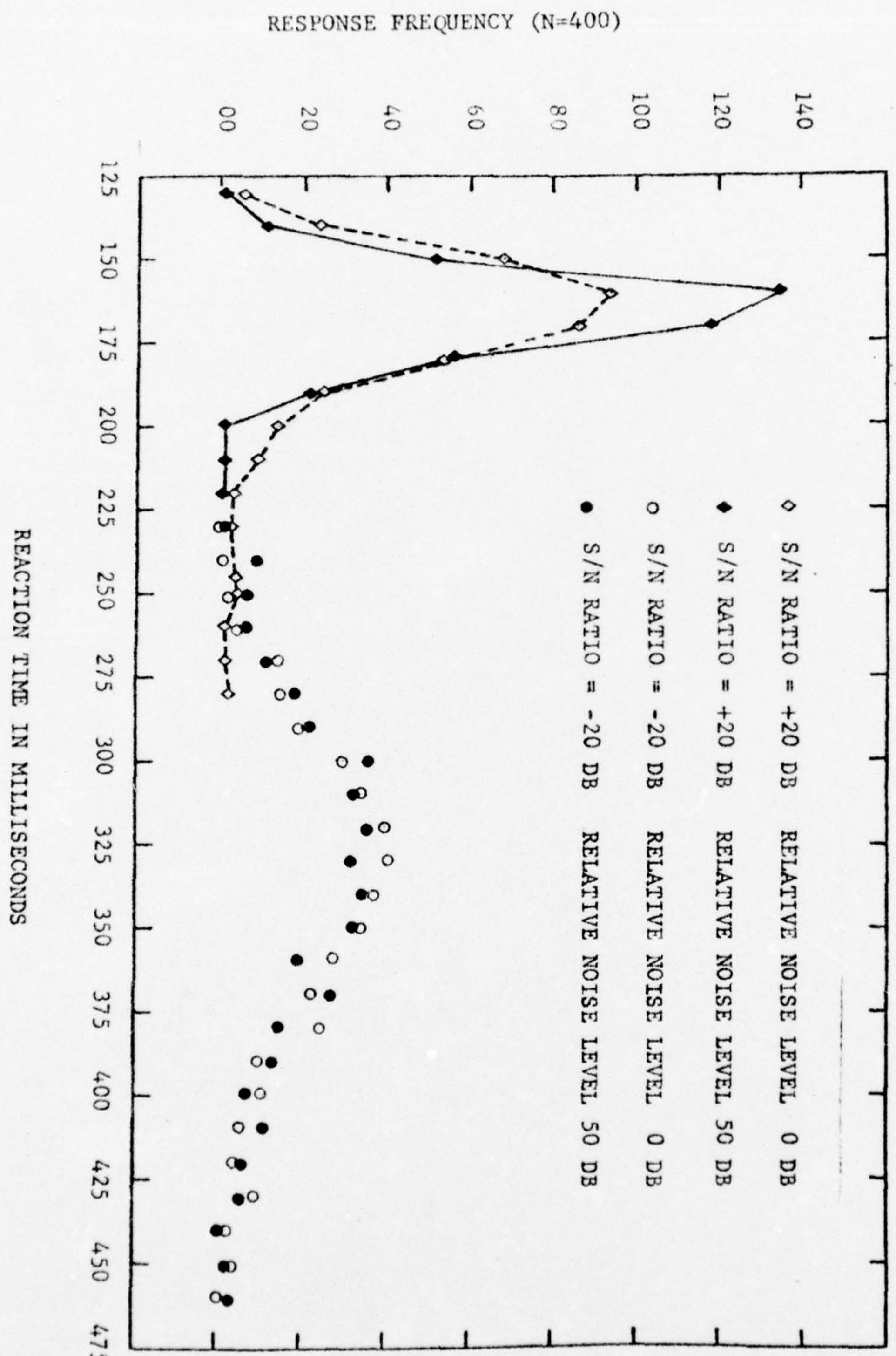

RESPONSE FREQUENCY (N=400)
00
20
40
60
80
100
120
140
125
150
175
200
225
250
275
300
325
350
375
400
425
450
475
REACTION TIME IN MILLISECONDS
◇ S/N RATIO = +20 DB RELATIVE NOISE LEVEL 0 DB
◆ S/N RATIO = +20 DB RELATIVE NOISE LEVEL 50 DB
○ S/N RATIO = -20 DB RELATIVE NOISE LEVEL 0 DB
● S/N RATIO = -20 DB RELATIVE NOISE LEVEL 50 DB

Fig. 3

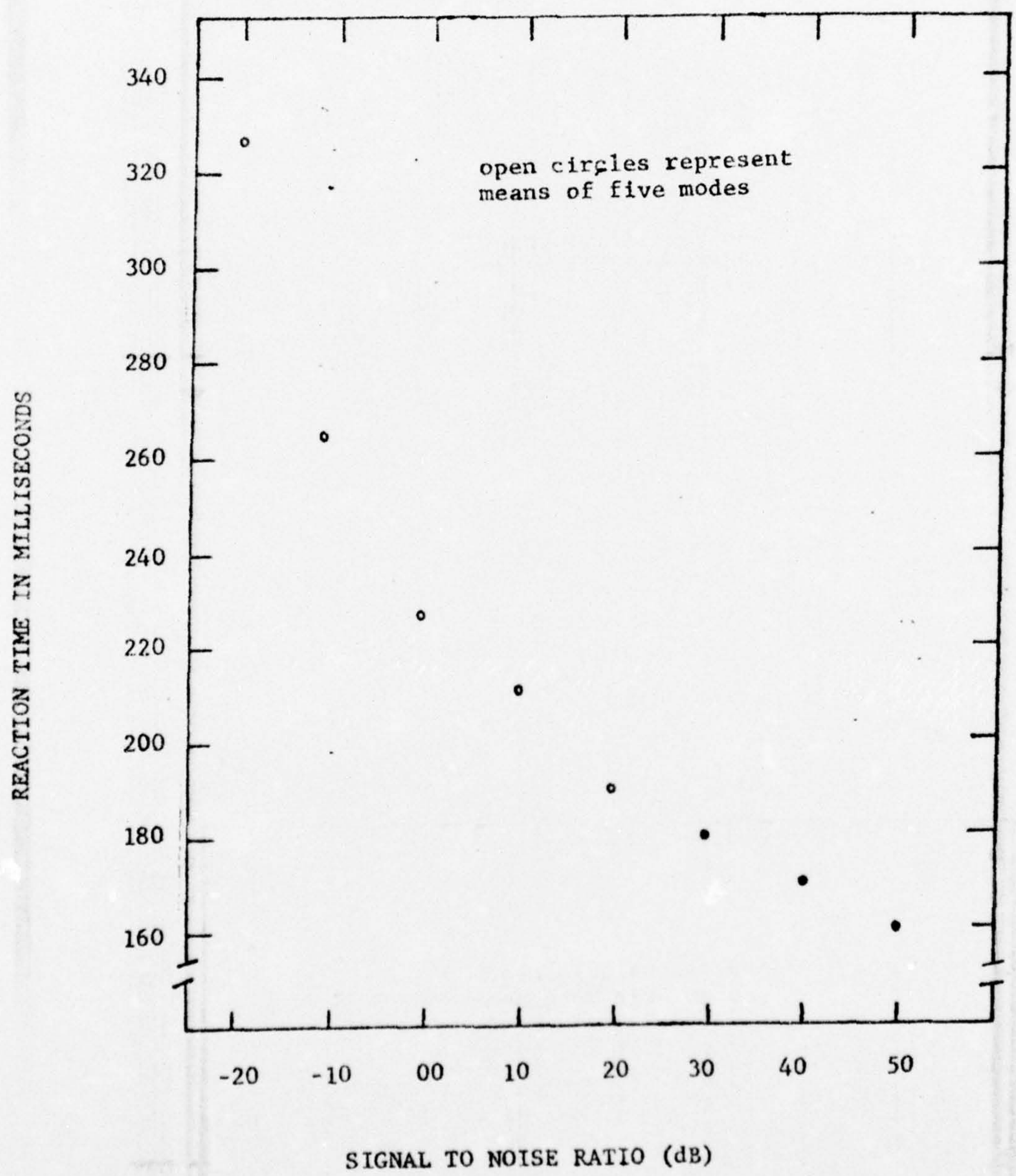

open circles represent
means of five modes
340
320
300
280
260
240
220
200
180
160
REACTION TIME IN MILLISECONDS
-20
-10
00
10
20
30
40
50
SIGNAL TO NOISE RATIO (dB)

Fig. 4

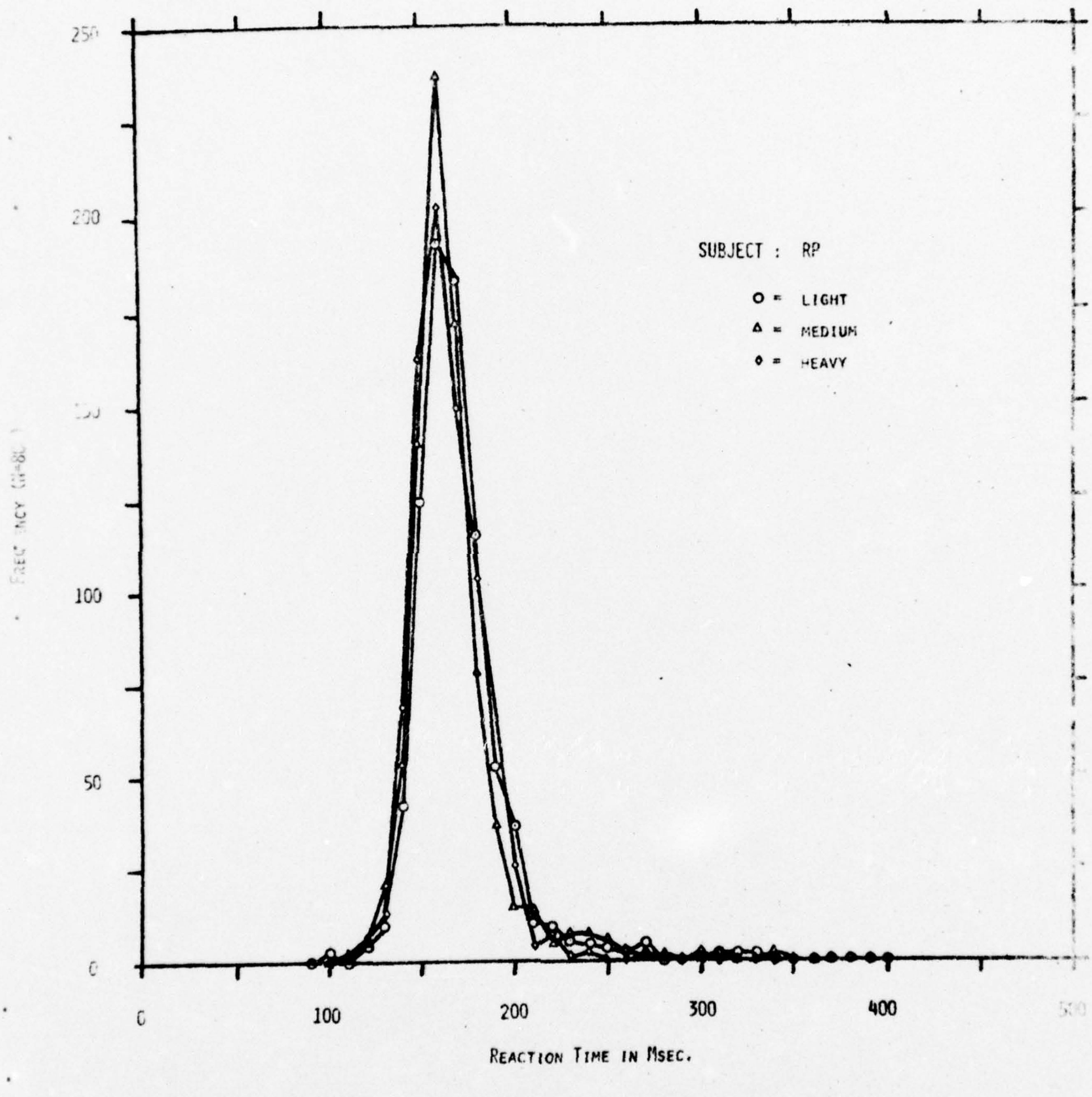

250
200
100
50
0
0
100
200
300
400
SUBJECT : RP
O = LIGHT
Δ = MEDIUM
◊ = HEAVY
REACTION TIME IN MSEC.

Fig. 5

1) a threshold model, the reaction time process begins when the "signal component" reaches or exceeds a particular threshold level relative to the "noise."

2) an integration model, the reaction time process is instituted when the integral of the "signal information" reaches a prescribed magnitude relative to the "noise".

To date, the subtlety of the design problem has prevented us from distinguishing between these models even though in principle they yield distinguishable reaction time functions as a function of rise time. The central difficulty is related to the difficulty of estimating the additive constant in the reaction time process. That is to say, before we can apply either of these models we have to have a general model of the reaction time process itself so that we can distinguish the parameters associated with the reaction time process from the parameters associated with the signal integration process. These studies are continuing on a low level making use of instructional budget funds for their performance. Consequently it may be some time before we are able to report in detail on these aspects of the reaction time research.

Simultaneous with these studies of the simple reaction time, other studies of sequential reaction time have been performed since the original work reported by Brief, Owens, and Galanter. This new work, a primary contribution of Russell Adams, studied the capability of the individual to control the inter-response time by use of appropriate band pay-offs or sequential contingencies. Some results shown in Figure 6 demonstrate that without question, individuals are capable of adjusting inter-response times with a precision of about five percent (at long IRT's) between 20 and 90 msec. Notice therefore that people are able to adjust their inter-response times at speeds that are all consistently faster than the minimum simple reaction time. It is this unusually provocative result that has convinced us of the autonomous nature of integrated acts, and the capability of human beings to organize acts with components that follow on each other at rates many times faster than the "call-up" time of a particular response. It is this organizational capability that leads us to believe that the theory of ballistic structure for complex acts that we postulate in this section is a plausible alternative to the classical feed-back view of large scale behavior.

Psychophysical Scaling

Our experimental studies of psychophysical scaling have taken two lines. Theoretical considerations have moved in novel direction. We review first experiments performed for the direct estimation of psychological scales of various social and physical events. The first of these scaling efforts were directed toward the construction of utility functions for monetary and non-monetary events. We have reviewed some of the findings from this work in the first section of the present report.

A second class of experiments was undertaken to connect category judg-

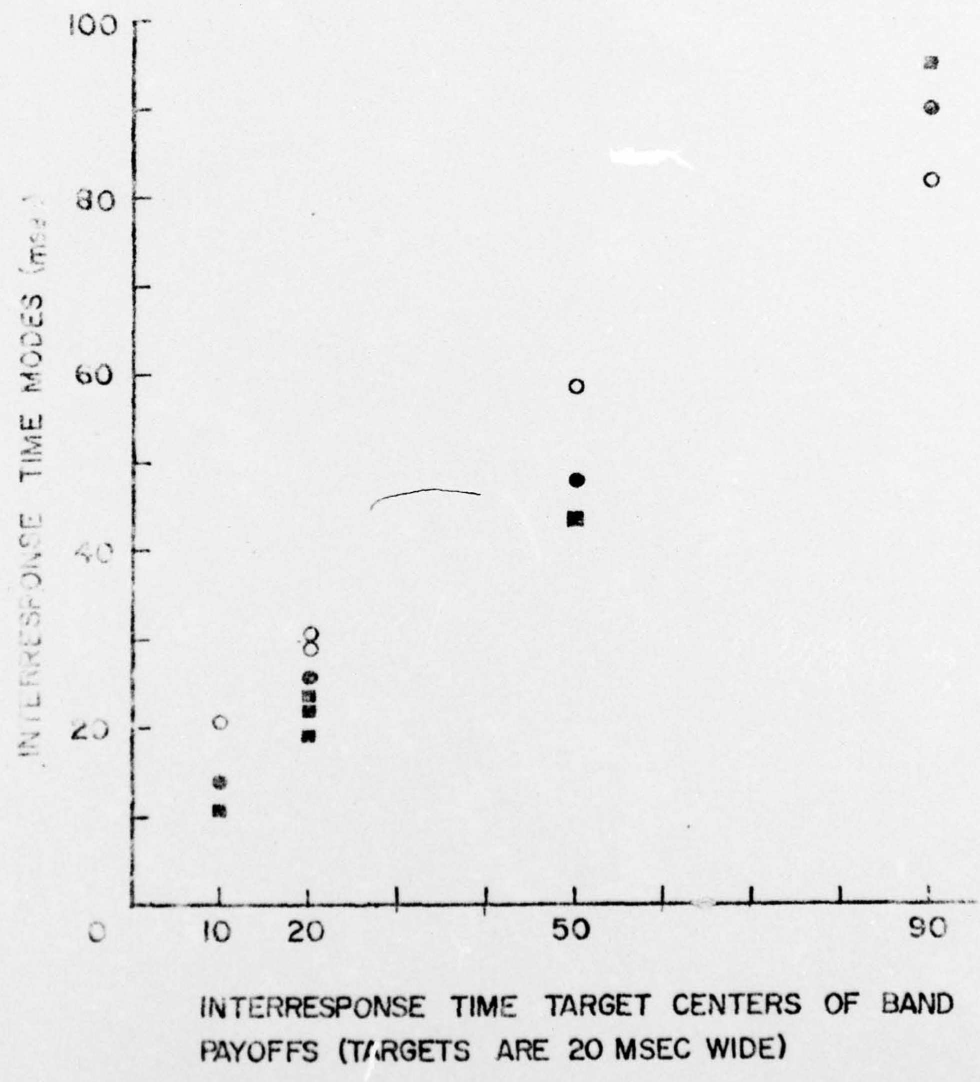

100
80
60
40
20
INTERRESPONSE TIME MODES (msec)
0
10
20
50
90
INTERRESPONSE TIME TARGET CENTERS OF BAND PAYOFFS (TARGETS ARE 20 MSEC WIDE)

FIG. 6

ments, the most widely used form of psychological scaling, to magnitude estimations. This effort to connect the two forms of psychophysical scaling represents a continuation of the original work by Stevens and Galanter (1956), and Galanter and Messick (1961). In these studies, we demonstrated that simple forms of category scaling (Likert scales) were non-linear functions of magnitude scales. Furthermore magnitude scales were shown to remain invariant over a wider class of experimental manipulations than category scales. It was on the basis of observations of this kind that Stevens concluded that magnitude estimation scales represented the "true" psychophysical functions. We have eschewed this argument in favor of demonstrating that these magnitude estimation functions are capable of predicting complex behavior patterns in other contexts. Thus, for example, we have used cross-modality matching (Galanter and Pliner, 1974) to validate further the utility scale functions of money against a variety of other psychophysical judgments.

In addition to such classical methods to validate magnitude estimation scales, Diane Jacobs and the Principal Investigator undertook a study of two models of category scaling data that partitioned the category judgment scales into a sensory and motivational process (Galanter and Jacobs, 1973). The sensory process within these two models could be construed as linear; as in Thurstone's theory--or hierarchical: a new proposal. The results of these experiments rejected the hierarchical model out of hand, a model in which we had a great deal of faith prior to the evidence. The linear model was strongly supported and in addition the stimulus parameters within this model remained invariant under pay-off manipulations, as predicted by the theory of signal detectability. Furthermore the response bias parameters in the category scaling experiments were shifted as if the subjects in the experiment were attempting to maximize their expected earnings or to maximize the utility transform of those earnings.

The applicability of ideas from the theory of signal detectability to the analysis of scaling studies added to our conviction that this theory possessed general notions that could and do illuminate many areas of behavioral research. To evaluate this conjecture we undertook a survey of the behavior science literature in which TSD had been applied to non-psychophysical problems. We are preparing a report of this literature review that will summarize these applications, and will also attempt to extract general principles to guide the application of this powerful theory into new areas.

Our review of approximately 200 applications of signal detectability theory demonstrates that the use of the theory has two main purposes. First, experimentalists have been able to demonstrate that what had been thought to be effects on behavior associated with sensory activities were in fact more accurately attributed to cognitive and motivational variables. In addition, certain kinds of effects that have been thought to be state induced, e.g., changes in taste thresholds as a function of hunger are shown to be merely alterations in response bias.

Our experiments on the development of psychophysical scales using magnitude estimation techniques have not been restricted to laboratory experiments. We have also completed a series of psychophysical scales of perceptual judgments under field conditions where the observer is undergoing dynamic transformation. We refer here to psychophysical scales of visual distance (depth) during the movement of an aircraft from some initial position to a runway touch-down zone. These studies were originally conducted to determine the perceptual basis for behavioral adjustments that were used to accomplish the landing maneuver by the pilot of an airplane. The results of many of these studies have been summarized in Galanter and Galanter (1973). The data reported in that article demonstrate the intrinsic non-linearity of distance judgments made by a pilot in a landing aircraft. In addition to these distance judgment experiments, we also conducted experiments in which pilots and observers made time judgments to touch-down points under the same environmental conditions. In these experiments we were able to show that time to touch-down judgments were essentially linear as a function of actual time. That means, that for constant velocities in an approach, time to touch-down was also a linear function of distance. Figure 7 shows this function.

This result, that the subjective distance as scaled by magnitude estimation to point of touch-down is a non-linear function of distance, whereas estimated time-to-touch-down is a linear function of distance led to a concern about what were the perceptual properties that guided the behavior in the performances involved in these activities. Further, we questioned whether switching from one judgmental basis to another might be a central factor in the disruption of such performance, and consequently the source of hazardous operations. Once we had recognized that the basis for the control of action may be constructed of multi-modal or multiple structured input information that could form the matrix for a ballistic act, our attention was directed toward the development of the theory of ballistic activity outlined in the previous section. In order to complement this theory of action, we saw the need to make a fundamental recharacterization of the nature of human perceptual functioning.

It is generally presumed that the sense organs constitute the primary mechanisms of perceptual analysis, integration, and organization (except for modality-specific central processing). The view of human action we now propose, however, requires a perceptual "receptor" that has the capability to perceive into time in the way that the eye perceives into space. Our primary notion is that such temporal perception is served by inter-sensory information primarily from the visual and auditory systems. These inter-modal effects are presumed to give rise to the experiences of past and future that may constitute what has classically been called "memory" and "imagination."

Generally speaking past research on inter-sensory and inter-modal phenomena have looked primarily for influences of one sense mode on the other (Klemmer, 1958; Adams and Chambers, 1962; Day and Beach, 1950). In the context of the present theory we propose that inter-sensory effects are to be construed as input parameters for some central imaginative-memorial perceptual mechanism. That is to say we presume that a variety of sensory data are mapped onto a single perceptual continuum, and that the continuum is representable in action as foresight or anticipation, and memory or review. It is such a common representation of inter-sensory information that enables a person to perceive plans and to execute actions based on temporal perception, and to contemplate alternative actions, and review his own past acts and percepts as part of his entire behavioral economy.

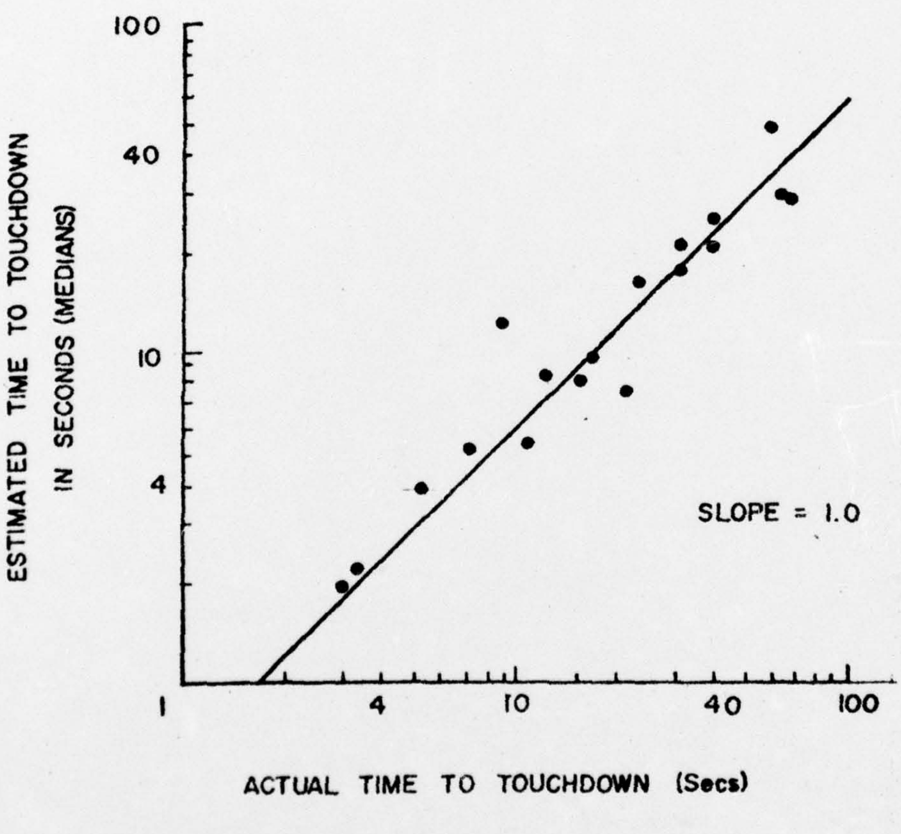

100
40
10
4
ESTIMATED TIME TO TOUCHDOWN
IN SECONDS (MEDIANS)
SLOPE = 1.0
1
4
10
40
100
ACTUAL TIME TO TOUCHDOWN (Secs)

FIG. 7

Such a notion, that a variety of sensory inputs are represented in some common form, is a current feature of the literature in studies of perception and attention. Modern attempts to demonstrate that the represenation of information from different sensory modes is reduced to a final common form on which action is subsequently based derive from early studies as Klemmer's (1958) work on time sharing between frequency coded auditory and visual channels, and work by Adams and Chambers (1962) on responses to simultaneous stimulation of two sense modalities. These classical studies have given rise to the more recent experiments that attempt to isolate the representation of the multi-modal inputs. For example the Shifrin and Grantham (1974) analysis of models for attention shows that attempts to attend to modality specific information does not improve performance. Furthermore, Auerbach and Sperling (1974) present a signal detection model and report evidence for a common auditory-visual space. This represents a straight-forward justification of our proposed unitary perceptual system that uses information from a variety of sensory modes. Finally, Marks (1974) shows that auditory and visual cross-modal matching experiments support the existence of what he construes as a cognitive machanism capable of manipulating dimensions of sensory experience. We would prefer to characterize such a mechanism as a perceptual processor. Such a characterization justifies an analysis of inter-sensory effects by experimental procedures that have been developed for the study of perceptual phenomena even though the apparent subject matter refers to remembered or anticipated events.

The ways that observations are conceptualized places a strong constraint on our understanding. Consider for example the concept of memory. A current view of the memorial function in human behavior is that memory consists of some sort of storage facility with addressing potential, so that information in some appropriately coded form, based on sensory input, can be retrieved on demand, when some address-like component of the sensory input is presented to the individual.

Such a storage-retrieval paradigm to turn human memory into a static library had a great deal to recommend it to Ebbinghaus (1885), because it lent itself to ingenious but easy experimental study. You put things in, then you see how much you can get out. The difference between the input and the output represented a degradation attributable to memory. The fact is that remembering things in this way is normally something that occurs on a theatre stage or in a psychological experiment. Memory itself must serve an ongoing, forward looking function, if it is to be of service to the active organism. The fact that in addition to this primary function it can also perform tricks, while interesting may not be too enlightening. Certainly to elevate such cleverness, e.g., the ability to recall a telephone number on demand, to the status of a central psychological process is to allow experimental procedure to dominate ones thinking.

In its primary role memory must represent how the perceptual system of the organism, (that is the processing of information and the characterization of activity) acts to "perceive" the past as well as the future in order to guide future action.

Part of the main conceptual point of our introduction of this new perceptual system is the conjectured mirror symmetry of the forward and backward looking temporal vision. Support for this conjecture can be provided by comparing experiments in which performance based on anticipation is compared with performance based on review. Exactly how these experiments will be performed in the laboratory is not clear, but as remarked above we have already engaged in field experiments in real life situations to assess the quality of anticipation judgments. Certain of these real life experiments consisted in varying the duty cycle of the visual availability of the aircraft environment to a pilot in which his anticipatory behavior is no longer under the control of his imagination.

Finally, a line of work in which we have only just begun is designed to determine whether the non-linearities in perceptual judgments are accompanied by non-linearities in performance based on those judgments. These "perceptual tracking tasks" have been recently instrumented and should begin shortly to generate data. The two modes that we are currently studying are the auditory intensity mode which is being tracked by movements of a pressure transducer, and a continuous visual distance judgment, which we are tracking with a stylus device. Preliminary data conform to classical results in this area. Our data suggest that given a modicum of training, linear performance outputs are available even though the perceptual functions themselves are non-linear. We interpret this to mean, <u>not</u> that the subject performs a non-linear psychic transform prior to the control of the output signal, but rather that the operator formulates a ballistic program to execute the responses based on an appropriate multiple structured matrix of input signals and their expected elastically transformed continuation. Experiments that interrupt the input signals at various points are currently being instrumented to assess the plausibility of these hypotheses.

In summary, research in the Psychophysics Laboratory at Columbia University over the past four years has yielded the following concrete insights and data:

1) We have determined with some precision the psychophysical function relating perceived desirability or aversiveness and incremental gains and losses of money.

2) We have show in the context of a signal detection experiment that the utility functions proposed in 1) above are not inconsistent with the pay-off control of human judgments in a psychophysical experiment.

3) Utility judgments for desirable and aversiveness non-monetary events can be obtained using the same techniques that we use for the monetary judgments, and the monetary judgments within the contexts of these non-monetary events recover the original parameters of the utility function.

4) People are able to generate sequential responses with inter-response times two orders of magnitude faster than the reaction time.

5) Inter-response times shorter than the simple reaction time can be adjusted over a wide dynamic range by appropriate variations

in monetary pay-offs.

6) Simple reaction times in the auditory modality have been shown to be independent of the force exerted upon the reaction key over two orders of magnitude.

7) Simple reaction times in the auditory mode are shown to depend on the signal-to-noise ratio and not the total acoustic energy.

8) Psychophysical judgments of the perceptual dimension of visual distance in a dynamic environment is a non-linear function of distance.

9) In these dynamic environments psychophysical judgments of temporal duration under constant velocity is a linear function of time.

10) We have formulated a new conceptual theory of human action and performance that construes large coherent and goal directed acts as ballistic, rather than feed-back controlled.

11) We are continuing experiments using our computer based facility to study problems of perceptual judgment and reaction time within the context of this new conceptualization.

Finally it is important to point out that during the course of this program the laboratory has acquainted approximately 22 undergraduates and nine graduate students with experimental techniques in which we have some competence. Three of our graduate students have received the Masters Degree for work conducted in the course of research under the subject contract, two of our graduate students have successfully completed their Ph.D. A third graduate student, Mr. John Allen Owens, who would have finished his Ph.D. during the term of this contract was killed in an airplane accident. His loss was deeply felt by all members of our laboratory and the Columbia University community.

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Dr. Herbert J. Mueller
Naval Air Systems Command
AIR-310, Research Admin.
Washington, D. C. 20361

Bureau of Medicine & Surgery
Operational Psychology Granch
Code 513
Washington, D. C. 20372

CDR Paul Nelson
Naval Medical R&D Command
Code 44
Naval Medical Center
Bethesda, MC 20014

Director, Behavioral Sciences Department
Naval Medical Research Institute
Bethesda, MD. 20014

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

CDR James Goodson
Chief, Aerospace Psychology Division
Naval Aerospace Medical Institute
Pensacola, FL 32512

Bureau of Naval Personnel
Special Assistant for Research Liaison
PERS-OR
Washington, D. C. 20370

Navy personnel Research and
Development Center
Management Support Department,
Code 210
San Diego, CA 92152

Dr. Fred Muckler
Manned Systems Design, Code 311
Navy Personnel Research and
Development Center
San Diego, CA 92152

L. CDR. M. O'Bar, Code 305
Navy Personnel Research and
Development Center
San Diego, CA 92152

CDR Robert Kennedy
Human Factors Engineering Branch
Code 5342
Pacific Missile Test Center
Point Mugu, CA 93042

Mr. Ronald A. Erickson
Head, Human Factors Branch, Code 4075
Naval Weapons Center
China Lake, CA 93555

Mr. Richard Coburn
Head, Human Factors Division
Naval Electronics Laboratory Center
San Diego, CA 92152

Dr. Robert French
Naval Undersea Center
San Diego, CA 92132

Dr. Jerry C. Lamb
Display Branch, Code TD112
Naval Underwater Systems Center
New London, CT 06320

Mr. James L. Long
Weapons Systems Research (N-332)
Naval Education and Training Command
Naval Air Station
Pensacola, FL 32508

Naval Training Equipment Center
ATTN: Technical Library
Orlando, FL 32813

Dr. Alfred F. Smode
Training Analysis & Evaluation Group
Naval Training Equipment Center
Code N-OOOT
Orlando, FL 32813

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

Mr. J. Barber
Headquarter, DA, DAPE-PBR
Washington, D. C. 20546

Dr. Joseph Zeidner
Dir., Organization and Systems
Research Laboratory
U. S. Army Research Institute
1300 Wilson Boulevard
Arlington, VA 22209

Dr. Edgar M. Johnson
Organizations & Systems Research Lab
U. S. Army Research Lab
1300 Wilson Boulevard
Arlington, VA 22209

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

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

Chief, Human Engineering Division
Aerospace Medical Research Lab
Wright-Patterson AFB, OH 45433

Dr. Donald A. Topmiller
Chief, Systems Effect. Branch
Human Engineering Division
Wright Patterson AFB, OH 45433

Lt. Col. Joseph A. Birt
Human Engineering Division
Aerospace Medical Research Laboratory
Wright Patterson AFB, OH 45433

Lt. Col. John Courtright
Headquarters
AMD/RDH
Brooks AFB, Texas 78235

Dr. E. Weiss
Office of Science Information Service
National Science Foundation
1900 Pennsulvania Avenue
Washington, D. C.

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

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

Mr. Edward Connelly
OMNEMII, Inc.
410 Pine Street, S. E.
Suite 200
Vienna, VA 22180

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

Dr. Robert R. Mackie
Human Factors Research, Inc.
Santa Barbara Research Park
6780 Cortona Drive
Goleta, CA 93017

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

Dr. W. S. Vaughan
Ocanautics, Inc.
3308 Dodge Park Road
Landover, MD 20785

Director, Human Factors Wing
Defense & Civil Institute of
Environmental Medicine
Post Office Box 2000
Downsville, Toronto, Ontario
Canada

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

Dr. David Zaidel
Road Safety Centre Technion City
Haifa
Israel

Prof. Dr. Carl Graf Hoyos
Institute for Psychology
Technical University
8000 Munich
Arcisstr 21
Federal Republic of Germany

ARI Field Unit - Leavenworth
Post Office Box 3122
Fort Leavenworth, Kansas 66027

Dr. William A. McClelland
Human Resources Research Office
300 N. Washington Street
Alexandria, VA 22314

Air University Library
Maxwell AFB, Alabama 31662