Perceptual-Motor Skill Learning[1]

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Living, moving, and behaving are almost synonymous terms Thus the study of motor and perceptual motor skill learning is in a very real sense the study of a large segment of the field of psychology However, there are two reasons why skill learning is not an especially appropriate or useful subclass of learning situation First, the theoretical framework within which skilled performance is now being viewed by most students of this topic is such that sharp distinctions between verbal and motor processes, or between cognitive and motor processes serve no useful purpose Second, since the processes which underlie skilled perceptual motor performance are very similar to those which underlie language behavior as well as those which are involved in problem solving, and concept formation, we should expect to find that the laws of learning are also similar, and that no advantage would result from treating motor and verbal learning as separate topics I realize, of course, that the distinction between verbal and motor processes is often a convenient one for practical purposes, and that the distinction has been common in theories of learning For this reason the first part of the present chapter is devoted to a general discussion of present theories regarding the nature of skilled performance and to an effort to establish the close relationship between verbal and motor processes

Interest in skill learning has fluctuated widely over the years, being rather high around the turn of the century and again at mid century, but remaining low from about 1910 to 1940 The most recent resurgence of interest in the topic of skill has resulted chiefly from influences outside of psychology I refer to the development of complex mechanisms for use in control, communication, and computing operations and to the parallel development of theory and mathematical models relating to such processes These models have proven to be very fruitful in stimulating psychological research, and in providing an integrative framework within which the similarities between different aspects of behavior, and various learning

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situations become more apparent The heuristic importance of these models is further justification for devoting the first part of this paper to a consideration of their implications for learning theory

Definitions and Taxonomy

Definitions

I realize that my view of the area encompassed by the term perceptual motor skill may differ from the views of many students of human learning So a few pages devoted to specification of some defining operations and to the development of background information are warranted

First of all, I intend to emphasize the term *skill*, rather than the terms perceptual or motor By a skilled response I shall mean one in which receptor-effector feedback processes are highly organized, both spatially and temporally The central problem for the study of skill learning is how such organization or patterning comes about

The matter of what muscle groups are involved in a particular behavioral sequence often is quite incidental and certainly no more important than the question of which retinal elements or which segments of the basilar membrane are involved in detecting a stimulus pattern The more relevant issue for an understanding of skill is the nature of the spatial temporal organization of receptor effector feedback processes, which often are relatively independent of the specific receptor or effector elements initially involved

One of the clearest expositions of the view of skill to which most recent workers in the field subscribe was provided by Lashley (1951) in his Hixon Symposium lecture on "The Problem of Serial Order in Behavior," where he dealt with the "orderly arrangement of thought and action " Advocating the commonality of different forms of learning and learned behavior he argued (1951, p 113) that

> Certainly language presents in a most striking form the integrative functions that are characteristic of the cerebral cortex and that reach their highest developments in human thought processes Temporal integration is not found exclusively in language the coordination of leg movements in insects the song of birds the control of trotting and pacing in a gated horse, the rat running a maze the architect designing a house, and the carpenter sawing a board present a problem of sequences of action.

Later, in discussing the generality of the problem of temporal integration, which he referred to as the 'syntax of action," he argued that "not only speech but all skilled acts seem to involve the same problems of serial ordering, even down to the temporal coordination of muscular contractions in such a movement as reaching and grasping" (1951, p 123)

Spatial temporal patterning, the interplay of receptor-effector feedback processes, and such characteristics as timing, anticipation, and the graded response are thus seen as indentifying characteristics of skill. Examples of such behavior may be found on every hand. Some forms of skilled behavior involve gross bodily activities, such as walking, running, jumping, dancing, swimming, and balancing. Other forms of skilled behavior involve segments of the total response mechanism, as in reaching, grasping, and manipulating. A great many skilled activities in the life of typical human beings today involve the manipulation of tools and objects or the control of machines, as is the case in writing, typing, playing a musical instruments, sewing, driving a car, piloting an aircraft, playing tennis, throwing a ball, doing assembly work, or operating a rotary pursuit apparatus in a psychological laboratory.

The use of language, under this definition, clearly is a form of highly skilled behavior. However, in the interest of restricting the present topic to manageable proportions, language learning will not be considered as a primary problem, except insofar as it is necessary to redefine the topic of perceptual-motor skill so that its relation to verbal, ideational, problem-solving, and information storage (memory) processes and to conditioning, paired associate learning, etc., is clarified.

Taxonomy

Elements of skilled performance.—Emphasis on organization and patterning of a behavior process immediately confronts the theorists, and the researcher, with the question of how the processes under study are to be analyzed. I assume that some form of analysis is a necessary part of scientific study. Much of the present paper either deals directly with this question of the basis for analysis of behavior sequences or discusses data from experiments that appear to have handled the issue in a satisfactory manner.

Historically Robert S. Woodworth (1899) is clearly the psychologist whose views on this question have had the most lasting influence on contemporary thinking, although Fullerton and Cattell (1892), Craik (1948), Stetson (1905), Bartlett (1958), and Montpellier (1937), among others, have made important contributions.

In his later book on the *Dynamics of Behavior*, Woodworth (1958), extended his earlier (1899) view that the integration of behavior in the time domain can be understood in terms of "two-phase motor units," which usually occur in sequences or "polyphase motor units" under the integrating influence of "preset" and "retroflex," the latter being Troland's (1928) term for feedback.

There is general agreement that the two-phase motor units are the building blocks out of which are fashioned spatially and temporally organized motor sequences The act of jumping may be cited as a typical example of a unified sequence consisting of a preparatory act (crouching) followed immediately by the act itself Hitting a golf ball is another example, here the backswing is the first part of the two phase unit The total time interval consumed by such a behavior unit is usually short, often about half a second Polyphase motor units, in simplest form, consist of sequences of two phase units Walking and rotary pursuit perform ance are good examples Although these ideas are found in Woodworth's 1958 book, they are also clearly present in his 1899 paper on the accuracy of voluntary movement In the earlier paper, for example, he made explicit the idea, subsequently accepted by almost all workers in the field, that the pattern for a typical two-phase motor response is set up in advance of its initiation, and may be uninfluenced during its execution either by sensory feedback, or by new independent sensory inputs He also concluded that in very rapid polyphasic responses, such as tapping successive targets, more than one two-phase response may be pre formed and emitted as a unit In passing, and as preparation for later reference to the analogy between skill learning and the development of a specific program for a data processing system, it is interesting to note that the setting up of a two phase motor response, in advance of its initiation, corresponds in many ways to the calling up of a computer *subroutine,* and that a repetitive polyphase unit corresponds in computer phraseology to what is called a *loop*

With the two-phase movement as a starting point, several additional taxonomic distinctions can now be made Although we are concerned specifically with perceptual motor skills, many of the task distinctions are equally valid for other types of tasks

Task continuity —One of the most important general characteristics of a task is its spatial and temporal continuity Since input, output, and feed back may each vary independently with regard to continuity, many com binations are possible The magnitude of temporal or spatial discontinui ties may also be important Thus if discontinuities are so small as not to be discriminable, then in effect the task is continuous Conversely, if con tinuous tasks contain marked periodicities, then they may become discrete from the *S*'s viewpoint.

The source of pacing may also be an important task characteristic In either serial or continuous tasks the *S* may set his own rate (self pacing), as in typing or driving a car Or the task may be externally paced, as in taking dictation or in aiming at a moving target

Task coherence —The emphasis on spatial temporal patterning of be havior immediately suggests the importance of an adequate taxonomy for specifying the sequential organization of tasks The general term *coherence* will be used to identify this task dimension, and tasks will be considered to differ in degree of coherence. The two most commonly used quantitative indices of coherence include degree of *relative redundancy,* and degree of *autocorrelation*. As an illustration, the rotary pursuit task is 100% coherent or redundant (if one assumes a perfect time clock or time sense) once frequency, phase, and amplitude are specified. Normal language behavior is variously estimated at around 50% redundant. Tracking and information-handling tasks can be made to vary in coherence over wide limits, depending on the choice of input sequence by the experimenter, although it is seldom if ever possible in practice to produce a completely incoherent continuous signal (one which is unlimited in frequency). It should be noted in passing that there is a trend in many areas of learning research to substitute the concept of coherence for that of meaningfulness. Thus word association norms, and measures of the strength of population stereotypes in perceptual motor tasks can be viewed as defining the degree of coherence or stereotypy in the behaviors which *S*s bring to our experiments. It is as important to specify the coherence of response sequences as of stimulus patterns.

Complexity.—Related to coherence, but capable of independent definition and manipulation, is the complexity of a task. In simplest terms, complexity refers to the number of different stimuli, responses or transformation operations that are possible (in a statistical or probabilistic sense) or that are actually contained in some block of space or time (in a deterministic sense). Thus, the English alphabet is less conplex than the Chinese alphabet, and the 2 unit binary alphabet of a digital computer is even less complex. Similarly, the instrument panel of an automobile is less complex than that of an aircraft.

A *sequence* of binary symbols or a sequence of alpha numeric symbols may be either highly coherent or incoherent. The temporal intervals between significant events (or the component frequencies of a continuous signal) as well as the events themselves, may be coherent or incoherent, and the events may be closely or widely spaced in time.

Although there are important task dimensions in addition to continuity, coherence, and complexity, these three are sufficient to specify many of the most important general characteristics of perceptual motor tasks. It should be re emphasized however, that the defining operations for each of these dimensions are applicable to any sequence of stimuli or responses.

Theoretical Models

It is not possible, in this paper, to present a detailed framework for the study of skill learning. In particular, it is not possible to discuss adequately the three types of models which are stimulating much of the contemporary work in this area Nevertheless, a brief reference to each is necessary I shall assume some preliminary acquaintance with the models, and restrict my remarks to an emphasis on a few general concepts derived from each, especially those regarding control and communication processes which are most relevant for learning theory

Communication Models

Rather than viewing perceptual motor behavior as a series of motor responses made to reach some goal, it is possible, and I believe considerably more profitable, to view such behavior as an information processing activity guided by some general plan or program Information and communication concepts are now being applied to many kinds of processes and can easily be extended to models of skilled performance Information measures are useful in quantifying the processes involved in skills, but in themselves do not suggest any theory about human behavior or indicate the nature of the models that apply to human skills Analysis of the operation of an information flow or data processing *system,* however, has suggested several concepts that are beginning to exert a strong influence on psychological theory

The concept of *information processing* is one such general concept Thus skilled perceptual motor performance can be viewed as involving operations such as information translation, information transmission, information reduction, information collation, and in some cases the generation of information (or of noise) Information storage is also involved, of course

Central to all information processing is the general concept of *coding* A code consists of an alphabet plus a system of fixed constraints One goal of an informational analysis of behavior is to specify the codes involved in human behavior, including neurophysiological processes as well as the inputs to man s sensory channels and his response codes

It should be noted in passing that information codes may employ discrete or continuously variable signals However, most of the uses made of information measures and communication theory by psychologists have involved the assumption that man uses discrete codes i e , that he categorizes information

Emphasis on information processing and coding is one reason why the dichotomy between verbal and motor processes, such as between verbal and motor learning does not appear to be as important as it once seemed to be Man uses a very large number of information codes, and this in itself is an important topic However, the informational characteristics of any task can be considered independently of the particular code employed.

Control System Models

The feedback control system or servomechanism came into widespread use during World War II, although regulators and similar devices had been known long before. At about the same time, work on skill learning received a strong impetus as a result of military interest in selecting and training aircraft pilots, gunners, and operators of other complex machines. It is more than a coincidence that the pilot's job in many respects, corresponds to that of an autopilot, and that the variables which are considered by the design engineer in perfecting an automatic control system are analogous in many respects to the task variables which affect the learning of a pilot. Several very general concepts of significance for psychological theory have been borrowed from control systems, of which the autopilot is one specific example. F. V. Taylor (1957) called such very general models metaconcepts, referring to their usefulness in bridging the interface between physical and psychological science. They should be equally useful in revealing commonalities in the field of human learning.

The most generally used control system concept is that of *feedback*. As noted previously, the idea of feedback (called by such names as retroflex and backlash) is an old one in psychology. The concept of reinforcement in learning theory also emphasizes a form of feedback. But the use of the feedback concept in a precise sense is relatively recent. In particular, the precise specification of the nature of the feedback function and a distinction between input, feedback, and disturbance or noise is necessary before feedback theory can be made quantitative. In this connection, it is important to remember that an important class of control system processes are those performed by regulators, in which the input is a fixed reference quantity, rather than a variable. The maintenance of erect posture is such a regulatory process. Here, all of the stimulation to which a person is responding is either feedback or some form of disturbance. Driving a car on a straight road is also a regulatory process, the nearest we can come to identifying the inputs to a driver in such a situation is to specify the rules or instructions he has been given, plus the inferences we make as to his goals or purposes. Otherwise, he responds entirely to feedback which tells him about his previous errors.

Another useful control system concept is that of a mathematical representation of the relation of output to input, called a *transfer function*. Given such a mathematical specification of the dynamics of a system, control theory can be applied by the engineer in order to predict performance or to modify the system so as to optimize some desired property. Most problems in control system optimization center around questions of how to modify the system transfer function directly, if this is possible, or if not, how to adjust feedback so as to optimize system performance. With respect to feedback it should be kept in mind also that many different functions of the output may be fed back for comparison with the input. Thus feedback may consist of integrals or derivations of the output, or samples of these or other output values. As a corollary it appears that the human operator of a dynamic system must also learn the nature of the system dynamics and discover what behavior on his part will optimize system output. This is true regardless of whether the task is a very simple one like throwing a rock or a complex one like controlling an aircraft. Thus a rock has mass, the air offers resistance to its flight, and the rock-thrower must adapt to these simple ballistic characteristics. An aircraft, of course, has much more complex characteristics, not the least of which is that its responses to control inputs vary as a function of altitude, airspeed, weight of fuel aboard, and many other variables.

As is the case with an information system, a control system may be continuous or discrete. However, the continuous system has received greatest emphasis. Thus, the two models we have discussed are sometimes referred to as digital and analog systems, respectively. Of the two, the information system is probably the more general model, since any control task may also be viewed as a special case of an information-processing task.

Adaptive System Models

Since learning is an adaptive process, the usefulness of the two preceding models is limited by the fact that they are static, i.e., they do not change their characteristics as a function of experience. This limitation is overcome in large part by the adaptive system model, especially adaptive systems with memory (information storage) capacity.

Several types of adaptive systems are currently of interest to physical and biological scientists. One such group of scientists is studying adaptive feedback systems. Others are studying artificial intelligence, growing automata and the like. Still another group of investigators is studying the processes whereby stored program computers can be made to modify their own programs. Further extensions of the adaptive system concept will undoubtedly appear soon (see Gibson, 1960).

Basic to the adaptive system is the existence of hierarchical processes. Programs are provided for carrying out basic or routine functions, and other, higher-level programs or plans (see Miller, Galanter, & Pribram, 1960) are provided for modifying these lower-order ones on the basis of accumulated information. Also intrinsic to the successful operation of an adaptive system are three specific kinds of processes (*a*) one that insures variability in input or system parameters, (*b*) one that provides a criterion measure, and (*c*) one that results in the system changing or maintaining its program or parameters so that over time it will tend to achieve a performance level which is closer to the optimal One of the simplest such mechanisms is one that constantly searches for an optimum, but has a short memory so that it makes no use of previous search procedures and attacks each new problem in the same way The stored program computer does not have this limitation Newell, Shaw, and Simon have pointed out that

> The real importance of the digital computer for the theory of higher mental processes lies not merely in allowing us to realize such processes "in the metal" and outside the brain, but in providing us with a much profounder idea than we have hitherto had of the characteristics a mechanism must possess if it is to carry out complex information processing tasks' (1958, p 163)

The same writers also assert that many of "the vaguenesses that have plagued the theory of higher mental processes and other parts of psychology disappear when the phenomena are described as programs" (1958, p 166) The concept of behavior organization in skilled activities also becomes much clearer and more operational when defined in such terms

Adaptive processes may be continuous or discrete More commonly, lower-order processes may be continuous, while higher-order processes are discrete, i e , effect discrete changes in lower-order ones usually over a relatively long time cycle As an illustration, it was found in connection with early efforts to apply linear, static-model feedback theory to human tracking performance that over short periods of time and for limited task conditions human tracking behavior may be described adequately by means of a fixed linear model or simple transfer function but that over longer periods of time tracking behavior is likely to exhibit discontinuities and be highly nonlinear

For the student of learning, the most promising model of an adaptive process is that provided by the stored-program data processing system The subroutines of such a program may be modified, so as to become more efficient, or the higher level "executive" program, which calls up the various subroutines, may be improved However, the program itself is quite independent of the particular data on which it operates at a given time Such programs can be written for many different communication, control, and data processing tasks, varying from the processing of sensor inputs, to tracking and playing chess

A Composite Model

In summary, if one views perceptual motor skill as a composite of communication, control, and data-processing activities, then the perceptual-motor tasks that we ask *Ss* to learn can be specified by reference to the abstract properties of sequences of events or signals (such as their continuity, coherence, and complexity), to the dynamics of the system (as specified by its transfer function), to the nature of feedback functions, and to the subroutines and executive programs of an abstract data processing system. Within such a general framework it is also possible to employ several additional important concepts such as information coding and information transformation and processing, and, more important, to develop specific models of adaptive control and information handling processes. It remains to demonstrate how this general framework will aid us in understanding the nature of skill learning, and how general the framework is.

The first theoretical issue to be considered within this framework will be the one touched upon earlier, when the question was raised, What is the basic unit or element of skilled performance? The fundamental issue is the suitability of a discrete as contrasted with a continuous model of skilled performance.

The Continuity-Discontinuity Issue in Skill Learning

Learning theorists are familiar with one aspect of the continuity issue in learning. This is the question: Are learning changes gradual or sudden, continuous or discontinuous? An example is the notion of sudden or 'insightful' reorganization of behavior. The study of skilled performance raises another aspect of the continuity-discontinuity issue, an aspect which has already come up repeatedly in the preceding discussion of continuous (or analog) vs. discrete (or digital) models. Here the issue concerns both the continuity of learning or adaptive processes, and the continuity of underlying perceptual motor processes. This issue has interested many recent students of skilled performance.

The issue is an important one because the answer dictates the kind of model that is appropriate, and the kinds of experimental tasks and methods that are most appropriate for the study of skill. In particular, the generality of much current research on human information handling performance hinges on the answer to this issue. In short, are two theories of skill learning and performance needed, one for continuous and one for discrete tasks, or will the discrete model suffice for both types of tasks? The sources of evidence on this issue are diverse, and none of the data are highly conclusive We shall therefore review several lines of evidence briefly

Evidence on Continuity-Discontinuity

Limited capacity for discrimination, perception, and short-term memory —It is clear that most perceptual-motor tasks require discrimination (usually on an absolute basis), classification, and other perceptual processes, as well as short-term memory and response differentiation These processes are usually carried out under a certain amount of time stress Very significant, from a theoretical view, is the close agreement among estimates of the absolute capacities of individuals in accomplishing these different functions (see Miller, 1956, and Newman, 1959, for example) Capacity for absolute judgment of stimulus magnitudes, span of perception, short-term memory, capacity for the discrimination of proprioceptive feedback, and capacity for the reproduction of quick movements all seem to be very closely matched when viewed as information and control processes

Now this in itself is not conclusive evidence in favor either of the discrete or the continuous type of model However, it is entirely consistent with the concept of a system that handles information in discrete "chunks," that employs numerous steps which are accomplished in series, and that consists of matched components

Intrinsic periodicities in response patterns.—One of the first writers to raise the continuity issue in relation to perceptual-motor skill was Craik (1948) who observed highly consistent discontinuities in graphic records taken in continuous tracking tasks He concluded that *S*s who track a constantly moving target often show irregularities in their responses which recur once or twice a second Such irregularities are much more marked early in learning than later, as shown in Fig 1, which is reproduced from Fitts, Bahrick, Noble, and Briggs (in press) Unfortunately, several types of artifacts arise in connection with the use of such graphic records First, direct visual analysis of graphic records is highly unreliable, so that it is necessary to use autocorrelation or frequency analysis Second, the presence of periodicities in the *S*'s error record which are of the same frequency as the input tends to obscure any periodicities introduced by *S* himself Such effects are clearly shown in the error autocorrelation records in Fig 2 (from Fitts, Bennett, & Bahrick, 1957). As practice is continued, less and less of the target periodicity comes through in the error record, but any additional periodicities introduced by *S* also become less conspicuous A few efforts have been made to obtain autocorrelation records of error early in tracking tasks having zero or constant velocity inputs (thus avoiding the input frequency artifact), but this approach has not been sufficiently exploited to provide us with conclusive answers At present, therefore, the data merely suggest that *S*s may, at least early in a continuous tracking task, make intermittent corrections at a rate up to about 2 per sec, but we cannot be sure of the effect

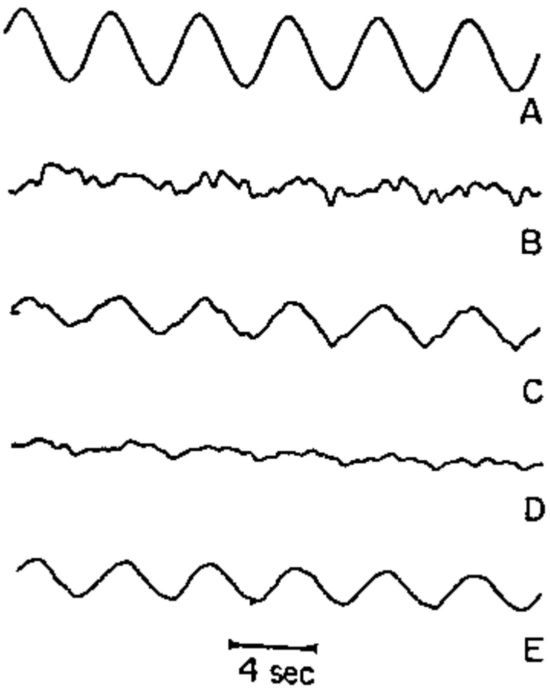
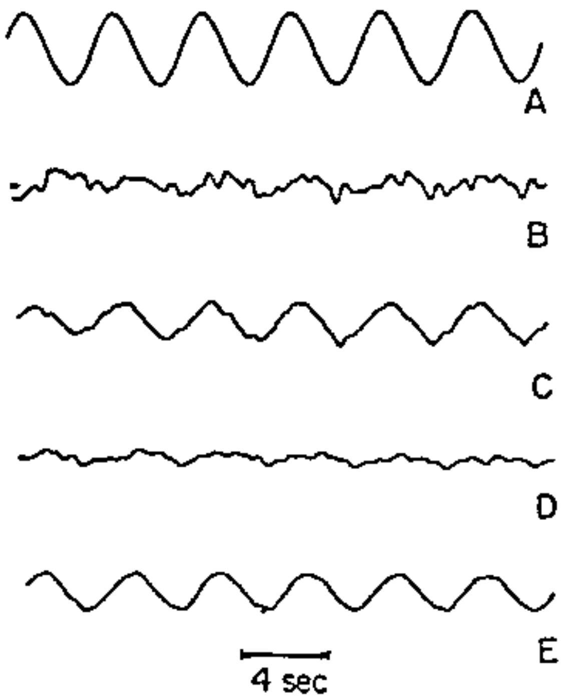


Fig 1 Periodicities in motor (tracking) responses to a slow (one cycle per 4 sec) sinusoidal target motion. Stimulus motion is shown in A C and E are the *S*'s responses early and later in practice, B and D are corresponding error records, early and later in practice Note that the irregularities introduced by the *S* appear to have a frequency of 1 to 2 per sec

Subjects are certainly able to learn to make fairly smooth, continuous movements, however These movement patterns may last for periods of at least several seconds or several cycles of a polyphasic response and can be carried out for a time with the eyes closed and no apparent exteroceptive feedback If we examine graphic records of such highly coherent responses carefully, however, especially as we push *S* to some limit in a visually controlled task, we may again note evidence of periodicity, such as periodic adjustments in the amplitude or frequency of responding every several cycles Such evidence is apparent, for example, in the "human frequency response' data shown in Fig 3 (from Noble, Fitts, & Warren, 1955), where *S*s were tracking a sinusoidal input of several cycles per second Woodworth (1899) observed similar periodic adjustments in *S*s' behavior in serial dotting tasks, and concluded that more than one biphasic movement may be pre selected and emitted as a unit

Reaction time and the psychological refractory period—One of the most commonly studied characteristics of perceptual motor performance been sufficiently exploited to provide us with conclusive answers At present, therefore, the data merely suggest that *S*s may, at least early in a continuous tracking task, make intermittent corrections at a rate up to about 2 per sec, but we cannot be sure of the effect



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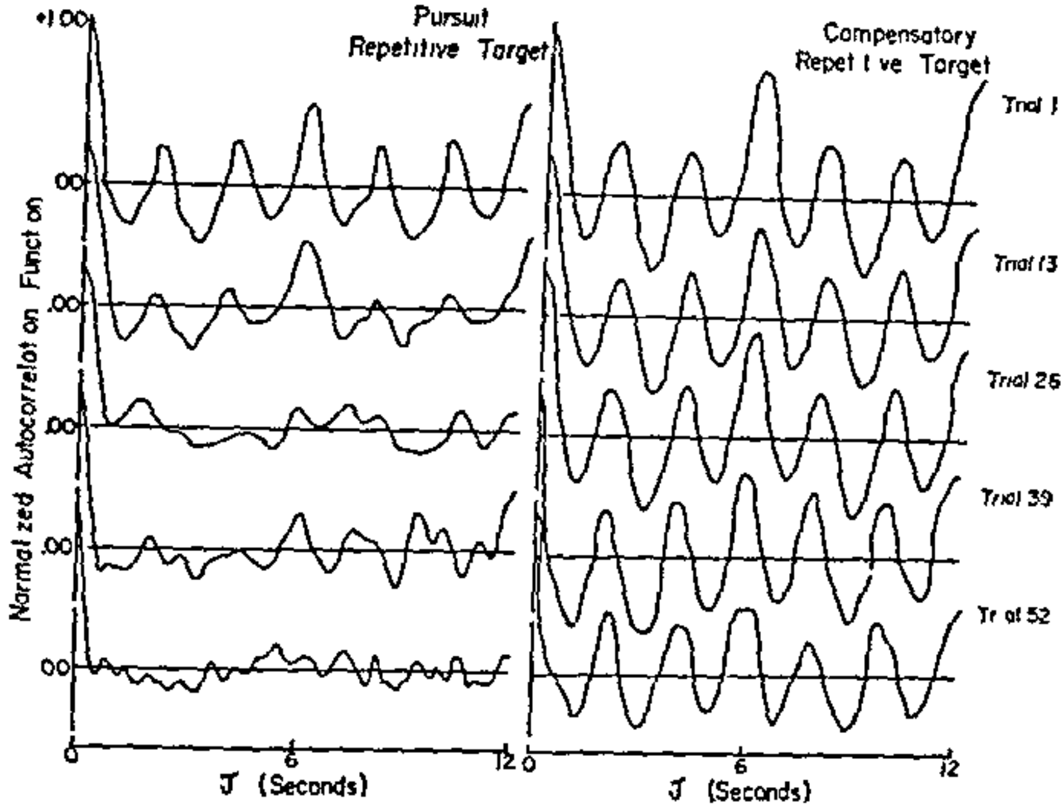

FIG 2 Autocorrelation records of manual tracking error records at different stages of practice, for a pursuit and a compensatory display (from Fitts, Bennett, & Bahrick, 1956)

is human reaction time in tasks where there is temporal or event uncertainty It is very difficult to measure reaction (lag) time in a continuous task But *it is* easy to present two discrete *stimuli in rapid succession* and to observe the effects of the second stimulus on the reaction time to the

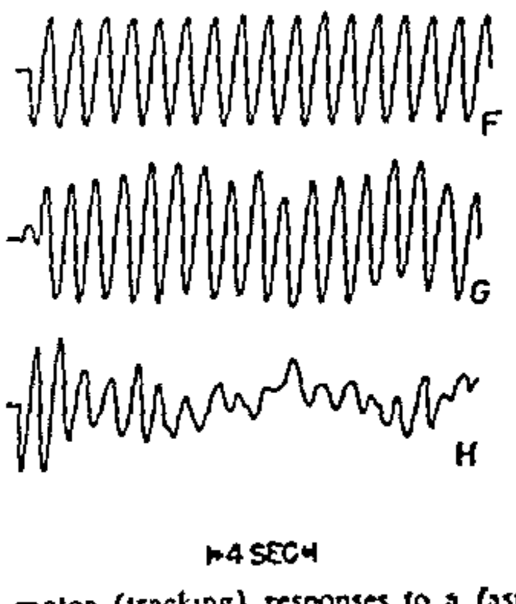

FIG 3 Periodicities in motor (tracking) responses to a fast (1 cycle/sec) sinusoidal target motion (F) The motor response of the *S* is shown in G and error in H Note the scalloping of the responses in G

first, and the effect of the first S–R event on the reaction time to the second stimulus At least it is easy in principle A substantial amount of research has been done on this problem The results clearly indicate that a preceding stimulus may delay the response to another stimulus which follows it if the interval between the two is between about 0 1 to 0 3 sec These results, however, have been interpreted both as an indication of the validity of the discrete model, and in terms of non-optimal set or expectancy

Hirsh and Sherrick (1961) report that two stimuli must be separated by at least 0 40 sec for their order of occurrence to be discriminated correctly 95% of the time Such data are congruent with the theory of a psychological refractory period, as advanced by Craik (1948), Hick (1948, Welford (1952), and others This theory suggests that the time for a single complete response cycle (discrimination of stimulus—response —discrimination of feedback) may be the basis for one kind of human intermittency

Information handling rate in continuous, serial and discrete tasks — Another line of evidence bearing on the continuity issue is the comparative rate of handling information in different types of tasks Most estimates of the upper limit of performance in speeded perceptual motor tasks have been around 25 to 35 bits per second for highly practiced *S*s in activities such as speaking reading, piano playing, and typing (Newman, 1959, Pierce & Karlin 1957) Although the upper limit of information handling rate varies markedly with several variables such as learning and coding (Alluisi, 1957), no one has as yet proposed that the difference between discrete and serial tasks, per se, is an especially important variable in this connection Speaking, silent reading, continuous tracking, and serial key-pressing for example, all give roughly similar estimates of peak performance capacity

A study by Brainard, Irby, Fitts, and Alluisi (1962) which used both a serial task having a 2 sec delay between each response and the next stimulus and a typical discrete reaction time task employing a 2 sec warning signal and 10 sec between stimuli provides a direct comparison of serial and discrete performance The results (see Fig 4) indicate small although fairly consistent differences in the two tasks Errors were slightly fewer for the discrete case, but response times were slightly shorter for the serial case, so that when rate of information transmitted is used as a criterion, performance is very similar in each of the four S–R tasks studied

Some years ago (Fitts 1954), I published some data on information rate in controlling the amplitude of movement in continuous, cyclical tasks Subjects attempted to make alternate hits on two targets, as shown in

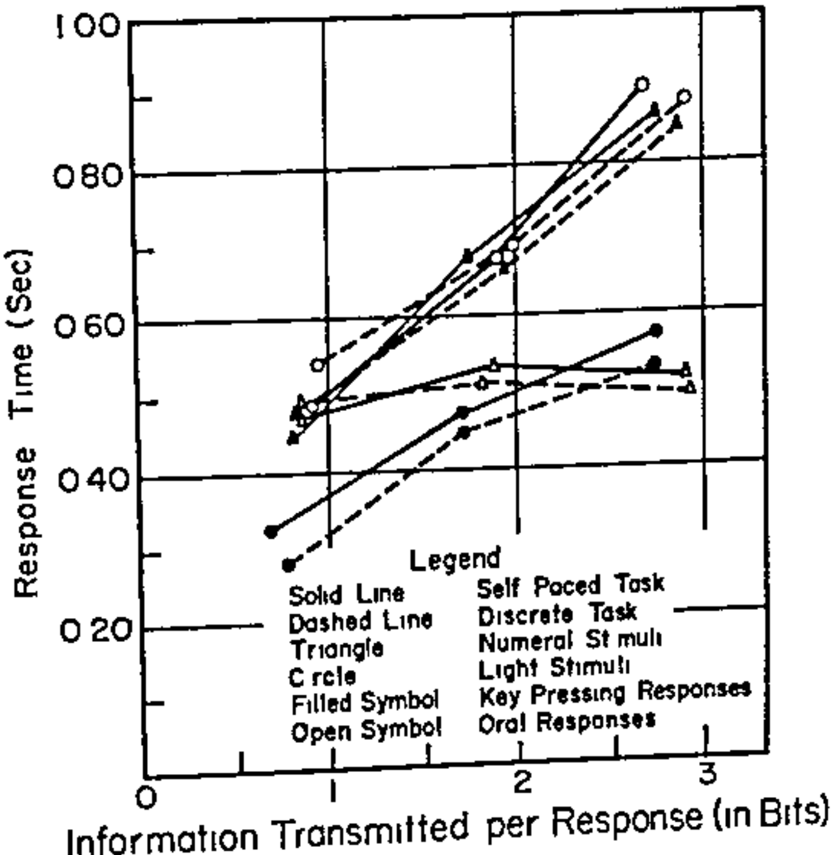

FIG 4 Reaction time as a function of S-R coding Note the similarity of times for self paced serial and for discrete tasks (after Brainard, Irby, Fitts & Alluisi, 1962)

Fig 5, working as rapidly as they could This can be classified as a continuous task (although hits were recorded discretely) since the two targets were continuously present and there were no enforced pauses or discontinuities Movement amplitude and required movement accuracy were varied systematically, and average time per movement cycle and errors were recorded Recently, we (Fitts & Peterson, in press) have completed a similar study using discrete responses in a typical 2 choice reaction time experiment The apparatus is shown in Fig 6 Subjects were sometimes required to hit one target as soon as possible after a light came on (knowing in advance which light-target pair would be used), at other times they were told to hit one of two targets as soon as one of two possible lights came on A 2-sec warning signal was used in both tasks, in the 1-choice task, the one stimulus light appeared with a probability of 0 5 after the warning Under these task conditions, reaction time was found to change very slightly as a function of the relationship between movement amplitude and accuracy The latter results for the two studies using continuous and discrete tasks are shown in Fig 7 In both studies the average time taken to execute a movement increased linearly as a function of the amount of information which the movement was required to generate However, the continuous task was considerably less efficient, i e , comparable movements took considerably longer than they did in the discrete task A likely explanation for this difference is that in the continuous task, *S*s had to insert a reaction time every few cycles of the movement in order to evaluate feedback data and keep the process under control This idea, of course, is consistent with earlier notions of Woodworth, Welford, and others regarding human intermittency Furthermore time in contact with the targets was included in the overall time for the continuous task, but was not included in movement time for the discrete case

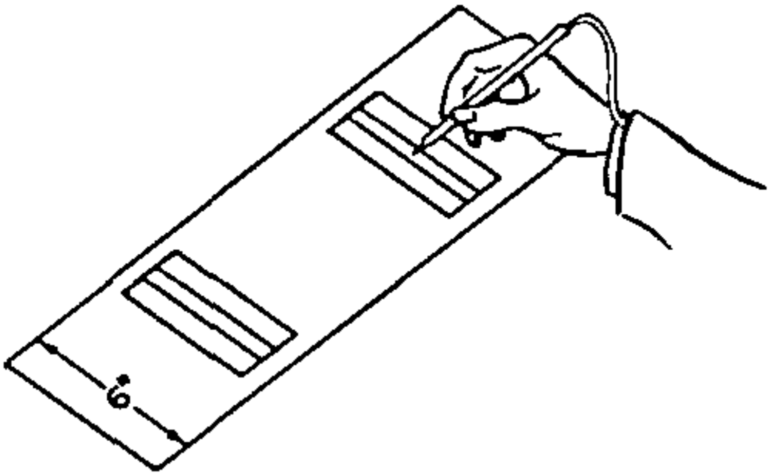

Fig 5 Apparatus used in studies of the effect of movement amplitude (A) and target width (required response accuracy W) on rate of responding in a continuous task (after Fitts 1954)

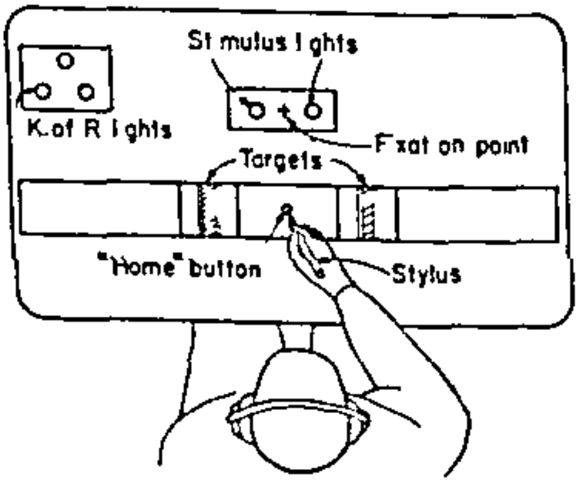

Fig 6 Apparatus used in studies of the effect of movement amplitude (A) and target width (W) on reaction time and movement time in a discrete two-alternative task (after Fitts & Peterson, in press)

Finally the data on eye fixations in reading and similar visual tasks should be mentioned The motor system of the eye is very efficient but its maximum rate is about five saccadic fixation movements per second,

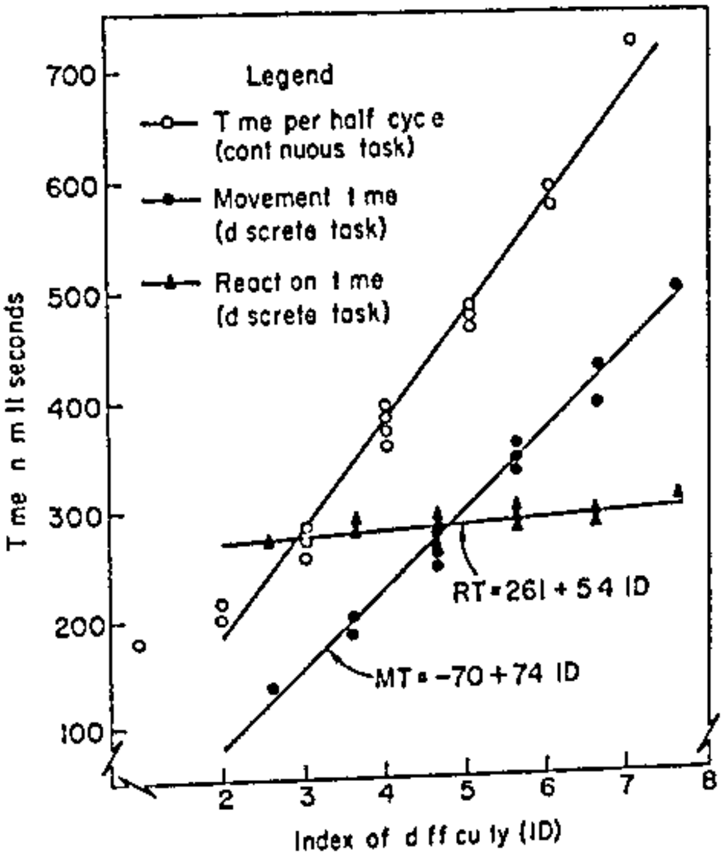

Fig 7 Reaction time and movement time for discrete responses as a function of the index of movement difficulty (ID) (after Fitts and Peterson 1964) The top curve (open circles) are comparable cycle time data for a continuous task (Fitts 1954)

and in many perceptual motor tasks, such as piloting an aircraft the rate is only about two fixations per second Visual input under such circumstances is clearly discrete, and since estimates of immediate memory capacity are that the *S* can hold only the information obtained in one or two fixations, the eye seems to be well adapted to use by a system which is operating discretely on one or two eye fixations worth of data per response cycle

Summary and Implications

Although the evidence is quite diffuse and none of it is very conclusive with respect to the continuity discontinuity issue, it does appear that a discrete model is adequate for describing behavior in continuous as well as in discrete tasks Viewing skilled performance as an information processing task, but making use of concepts borrowed from feedback and adaptive system theory, a model for perceptual motor skill learning might take the following general form (for a more complete discussion see Fitts 1962)

An adult or even a child of a few years of age, never begins the acquisition of a new form of skilled behavior except from the background of many already existing highly developed, both general and specific skills Thus the initial state of our model is not that of a random network, but an already highly organized system possessing language skills, concepts, and many efficient subroutines such as those employed in maintaining posture, walking and manipulating The number of such identifiable highly developed skills in an adult is certainly in the hundreds, each having its own executive program and library of subroutines, many of the subroutines being shared with other skills

Learning to swim provides a typical example of a skill that is learned against a complex background of already existing habits The first (hypothetical) step in such learning is the setting up of a general executive program What usually happens in such a learning situation is that *S* listens to instructions, observes demonstrations, and tries out different routines which he already has available, until somehow or other he gets started at the learning task Verbal mediation plays an important role in this early stage

The actual sequence of behavior processes employed early in learning varies with the type of activity, of course, but might be somewhat as follows The *S* observes or samples certain aspects of the environment, puts this information in short term storage after some recoding, makes a decision such as selecting an appropriate subroutine which sets up a response pattern, executes a short behavior sequence such as a biphasic or polyphasic movement, samples the internal and external feedback from this response plus additional stimulus information from the environment, recodes and stores this new information (in the process losing some of the information already in short term storage), makes another decision which might be to use a different subroutine, and so on As learning progresses, the subroutines become longer, the executive routine or overall strategy is perfected, the stimulus sampling becomes less frequent and the coding more efficient, and different aspects of the activity become integrated or coordinated (such as kicking, breathing, and use of the arms in swimming) In other types of perceptual-motor tasks, such as those which are less coherent than swimming, the improvement may take the form of strategies and decisions processes better adapted to the probabilities associated with stimulus sequences As learning continues, overall performance may come to resemble more and more closely a continuous process The overall program having now been perfected, frequent changes no longer need to be made in it However, subroutines may continue slowly to become more efficient, and the *S* to become increasingly able to carry on the entire behavior process while engaged simultaneously in other activities, with little or no interference between the two

Such a general verbal description of skilled learning probably sounds quite familiar to anyone who has read the older literature on this topic

Consider, for example, the following brief quotation from Bryan and Harter (1899, p 373) on the learning of telegraphy

> A plateau in the curve means that the lower order habits are approaching their maximum development but are not yet sufficiently automatic to leave the attention free to attack the higher order habits

One of the most important advances made in the years since Bryan and Harter's studies of telegraphy is clarification of what is meant by a program or plan (see Miller, Galanter, & Pribram, 1960) governing a sequence of operations The present writer has been working for some time on a computer program to simulate a hypothetical batter hitting a baseball, the batter having available sensors for sampling the flight of the ball, a computer for determining azimuth and trajectory, a memory for baseball "lore," a probability computer and the like, but operating in real (human) time with an assumed cycle time corresponding to a human baseball player This does not appear to be an appropriate time to unmask this particular automaton, but my own conclusion is that if a digital computer can be programmed to play chess against a human opponent, then it can probably be programmed to hit a baseball thrown by a good human pitcher, a skill not to be dismissed lightly, since in many respects it is much more complex than that involved in playing chess

In the remainder of this paper, skill learning will be treated as if the discrete model were the appropriate one I assume that my colleagues who like to enumerate stimuli and responses, to refer to the number of discrete reinforcements, and the like, will be pleased by this conclusion and will find it acceptable if I now sometimes talk about such things as rate of responding and frequency of reinforcement in a continuous tracking task Specifically, after a decade of research devoted chiefly to the study of skilled performance in continuous tasks, I have recently turned to the study of information handling behavior in serial and discrete tasks, but I believe that I am studying essentially the same basic perceptual motor skill processes as before Fortunately, as mentioned earlier, all of the task taxonomy which I shall employ is equally applicable to continuous and to discrete sequences of behavior

Phases Characteristic of Skill Learning

Skill learning is primarily a continuous process even though the fine grain structure of the performance itself may involve discrete operations Thus it is misleading to assume distinct stages in skill learning Instead, we should think of gradual shifts in the factor structure of skills, or in the nature of the processes (strategies and tactics, executive routines and subroutines) employed, as learning progresses The evolving process is revealed by the organization of behavior into larger and larger units, as Bryan and Harter (1899) emphasized, and toward hierarchical organization, as Miller, Galanter, and Pribram (1960) have recently emphasized in their discussion of motor skills and habits

Changing Factor Structure of Skills

Recent correlational analyses of performance at different points in skill learning reveal significant changes in the relationships among abilities both in different tasks and at different stages of practice in the same task Correlations between the first trial and successively remote trials become progressively lower, whereas correlations between the most recent adjacent trials become progressively higher Also, the factor structures of complex tasks change consistently with practice, indicating that ability requirements are different at different stages of learning (Bilodeau & Bilodeau, 1961, Fleishman & Hempel, 1954, 1955), as Bryan and Harter suggested long ago

Phases in Skill Learning

Early phase—The earliest phase of skill learning in an adult may be of very short duration in simple tasks, covering only the time required to understand instructions, to complete a few preliminary trials, and to establish the proper cognitive set for the task

Skill learning processes during this phase are undoubtedly very similar to those involved in the early phases of rote learning Underwood and Schulz's (1960) discussion of the response learning stage of rote learning applies equally well to skill learning, especially when the responses are heterogeneous and the total situation is new Response integration is especially important when the new task requires the simultaneous use of two previously differentiated sets of responses, or response subroutines For example, response response compatibility effects are important determinants of difficulty in the learning of complex tasks involving both hands or hands and feet, as when a typist first tries to use the foot pedal to govern the play back of a dictating machine when a beginning student of music first tries to produce different rhythms with the two hands, or when a novice first tries to coordinate breathing and arm strokes in swimming

Intermediate phase—The intermediate phase of skill learning resembles Underwood's "hook up" or associative stage of rote learning Two kinds of mediation processes appear to be important at this time One mediates the formation of specific associations and learning to respond to specific cues The other involves cognitive set learning discussion of which will be deferred briefly

An unpublished experiment completed recently by Fitts and Switzer illustrates clearly the role of mediating associations in learning and also shows the close relationship between perceptual-motor and verbal learning The task was to make a vocal response as soon as possible after the exposure of a picture Twelve pictures were selected to represent objects whose names were of highest frequency in the Thorndike-Lorge word list, with the restriction that each name begin with a different letter of the alphabet The pictures are shown in Fig 8 They were exposed by the opening of a double-bladed mechanical shutter Vocal reaction time was detected by use of a boom microphone and voice key and measured to the nearest 01 sec The effects of two variables were studied—number of alternative stimuli (12 vs 3 pictures), and directness of the verbal mediation All responses involved saying a letter of/the alphabet In one case (direct mediation), the response was the first letter in the familiar name of the object In the other case (indirect mediation), the response was one of the other 11 letters (selected randomly) Note that neither response is one that *S* would ordinarily make The population stereotype is to give the name of the object not a letter of the alphabet In one case it is assumed that the required response was 'hooked up" to the stimulus, by an associative chain consisting of Stimulus → Familiar object name → Vocalization of first letter of name In the other case, presumably the associative chain involved at least one additional step Stimulus → Familiar object name → Some other name → Vocalization of the first letter of the other name When interrogated at the end of the experiment, most *S*s reported such a chain of associations Subjects were pre-trained to a criterion of two correct trials by an efficient training method, and then reaction times were taken during five 30 min testing sessions Reaction time data are

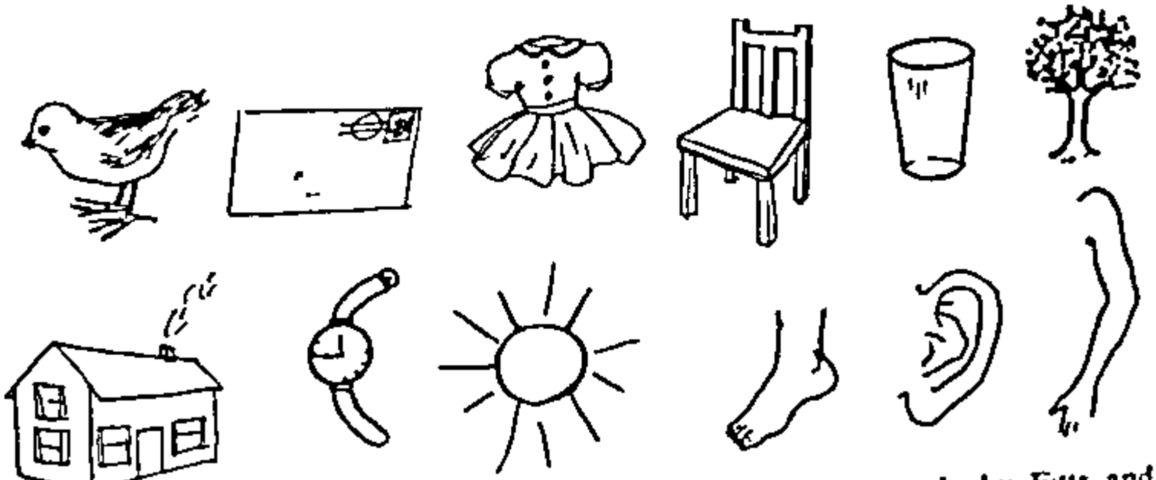

FIG 8 Pictures of common objects used in an unpublished study by Fitts and Switzer The responses to these pictures which were assumed to be mediated by "familiar associations were bottom row, left to right, H, W, S, F, E, A top row B, L, D, C, G, T Unfamiliar associations employed the same set of letters but different pairings

are each for a single *S* and thus are free of the artifacts that frequently appear in group data. Each of these studies, by a different investigator, indicates that the log-log relation between time and trials is essentially linear after the first few thousand trials.

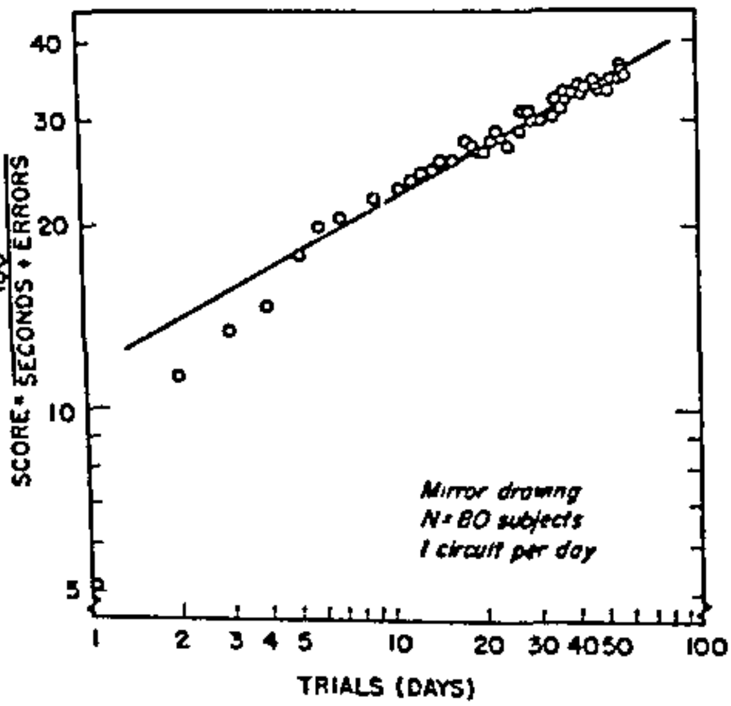

FIG. 10. Gradual improvement in mirror drawing with long-continued practice (after Snoddy, 1926).

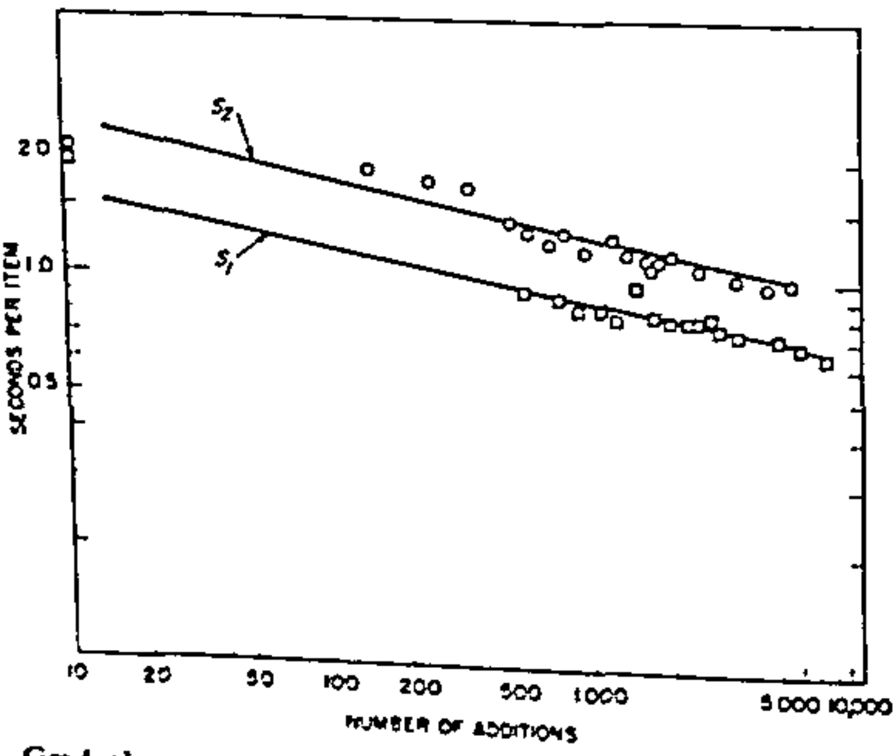

FIG. 11. Gradual improvement in mental arithmetic with long-continued practice (after Blackburn, 1936).

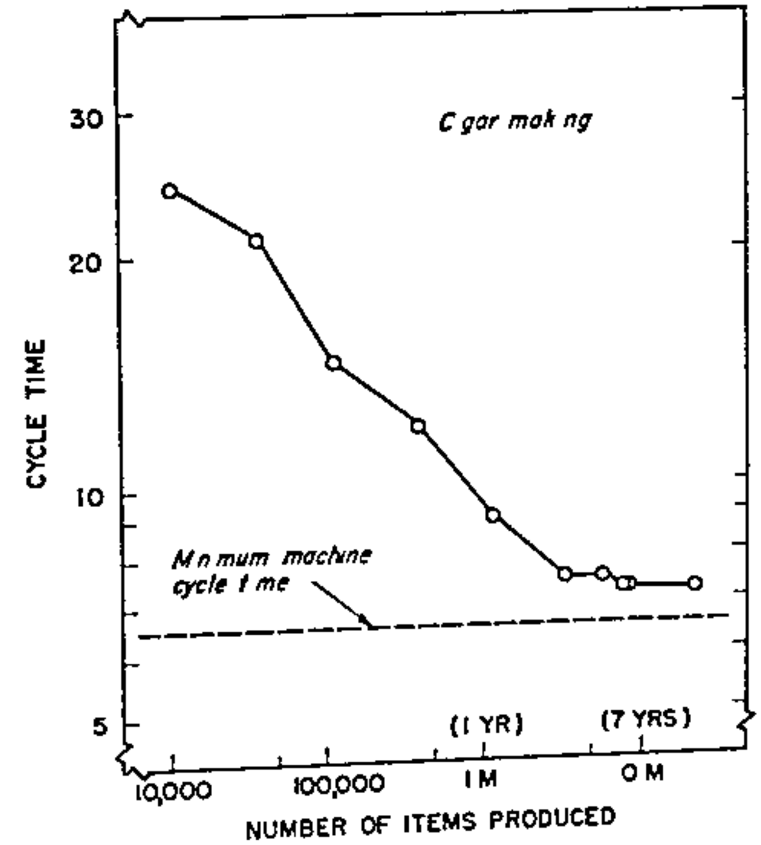

FIG 12 Gradual improvement in the performance of an industrial task over several years of work (after Crossman 1959)

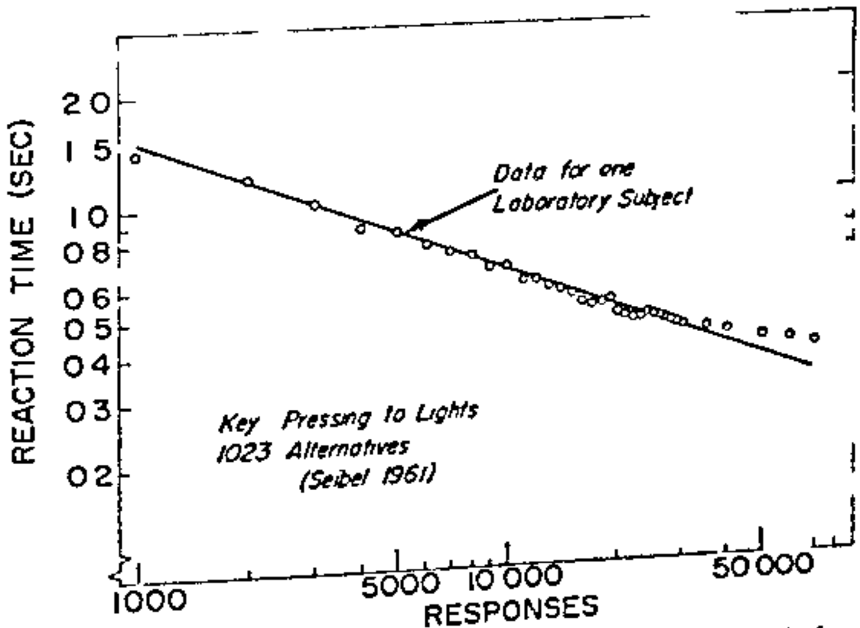

FIG 13 Gradual improvement in a 10 bit key pressing task with long-continued practice (after Seibel as reported in Klemmer 1962)

Another line of evidence regarding the continued improvement of performance in perceptual motor skills comes from case studies of the conditions of practice necessary for attainment of championship performance in individual athletic competitions, such as skating swimming diving and track events, in games of skill such as bowling or golf, in competitive sports such as baseball and football, and in artistic performances such as singing and playing musical instruments It is very rare for peak performance in any of these activities to be reached short of several years of intensive, almost daily practice And the fact that performance ever levels off at all appears to be due as much to the effects of physiological aging and/or loss of motivation as to the reaching of a true learning asymptote or limit in capacity for further improvement Thus, in the case of skill learning, the asymptote, along with the plateau, must be viewed as an exception, rather than an accepted phenomenon of learning

Two kinds of evidence from developmental studies also indicate that perceptual motor behavior develops slowly on the basis of a great deal of practice Restriction of early visual motor behavior (in the case of animals) provides one kind of evidence Riesen and Aarons (1959), for example, find that animals whose only early visual experience is gained with the head and body immobilized subsequently have great difficulty learning to control their own locomotion by the aid of vision The other line of evidence comes from studies in which the natural relation between visual cues and motor behavior is disturbed, (Snyder & Pronko, 1952, Ruhle & Smith, 1959) or in which *S*s are asked to perform visual motor tasks in which the required responses are contrary to cultural patterns and population stereotypes (Fitts & Seeger, 1953) Although subjective reports often indicate that the old visual movement habits may be unlearned and replaced by new ones after a few days, precise measures of skilled performance show that decrements persist over the maximum periods of time yet studied (see Fig 14)

Cognitive Aspects of Skill Learning

Specific S–R Associations vs Cognitive Set Effects

The issue of specific versus generalized learning effects, i e , the learning and use of specific associations versus the learning and use of generalized sets or concepts, is an old one in learning theory and has its counterpart at all stages of skill learning The issue seems to be largely one of relative importance In the case of perceptual motor skills the importance of cognitive or mediational processes relative to simpler association processes appears to depend primarily on one of the task variables mentioned earlier —task coherence In a highly coherent task, regardless of the length or complexity of the sequence, stimulus and response patterns are essentially fixed and it would seem that the middle and late stages of the learning of such fixed response sequences should reflect a process similar to that governing the associative phase of rote learning and conditioning In the case

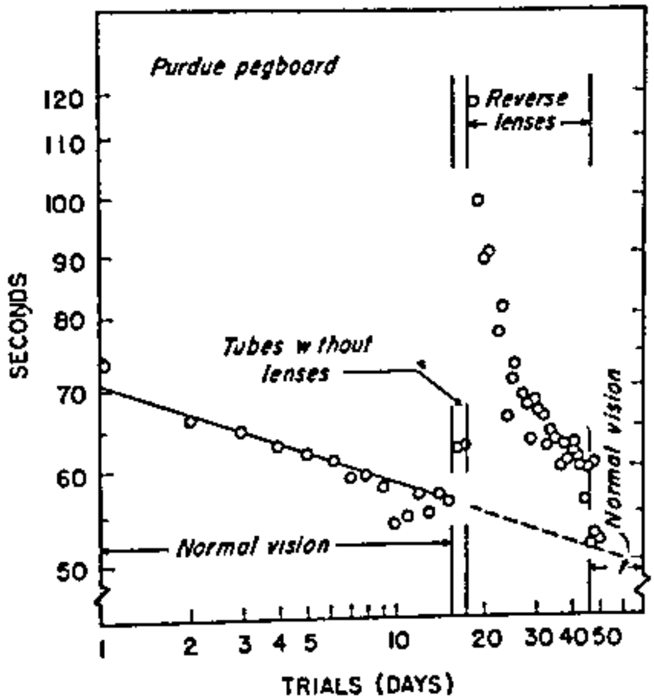

FIG 14 Effect of the wearing of reversing lenses on a task requiring precise visual control of motor responses (after Snyder & Pronko 1952) Note that at no time did performance while wearing the reversing lenses reach the earlier level achieved with normal vision or attained one day after their removal

of less coherent tasks, however, very large numbers of response patterns are involved and probabilistic rather than deterministic rules govern events Here it seems reasonable that strategies and executive routines become increasingly important, probability densities have to be learned rather than discrete events, and the generalization of learning is mediated increasingly by cognitive sets

The learning of language and perceptual motor skills frequently requires the development and use of very general cognitive sets As an illustration, an individual often responds to the same word very differently depending on the context He adjusts quickly to instructions such as "now respond with a word having the *opposite* meaning," or "tell me the *class* to which the following word belongs' Similar instances of the importance of set are observed in the realm of perceptual motor behavior Lashley used the term 'syntax of action" to emphasize this relation For example, the response of an aircraft pilot to a statement such as "right wing down' (which can mean two opposite things) will depend on whether the statement is interpreted as a command, or as a report of error Similarly the movement of a needle on a dial can also be interpreted in two opposing ways, and the set of the observer will often determine whether he moves the related control in one direction or the other

The point to emphasize here is not so much that people develop cognitive or learning sets, or show adaptation level phenomena in perceptual-motor tasks, but that they can develop many different cognitive sets, can switch from one to another readily, and can include the same stimulus or response elements as members of many different cognitive sets

Cognitive Set Learning in Skills

Viewing perceptual motor performance as an information handling skill suggests several ways of studying cognitive set learning its role in skilled performance, and its relation to stimulus and task variables Several of these topics will now be considered.

Compatibility effects and number of alternatives—S–R compatibility effects are ordinarily defined (Fitts & Deininger, 1954) in terms of performance or learning changes attributable to the interaction (congruence) of stimulus and response sets [2] They can easily be demonstrated in experiments where two or more sets of stimuli are paired with two or more sets of responses Recently it has become apparent that the absolute magnitude of such effects tends to be greater, the greater the complexity of the task (e g , the greater the uncertainty per stimulus) Griew (1958) has pointed this out, and some recent unpublished experiments by Fitts and Peterson show it clearly In Fig 15, for example, are shown three functions relating choice reaction time to average amount of information transmitted per response The bottom curve is for the most highly compatible task we have studied—pointing one's finger at a light The *S* simply moves his finger from a starting position and touches whichever one of a set of *n* lights is presented by *E* In this task reaction time increased by only 017 sec for each 1-bit increase in stimulus uncertainty A second function was determined for the same pointing responses, but with the hand and the response targets hidden from view by a screen and with the lights which served as stimuli located on a vertical panel in front of *S* Reaction times are still quite rapid but slightly slower than before, and the effect was greater for 9 than for 3 alternatives The top curve in Fig 15 is included for comparative purposes it is based on Hick s (1952) data where the task was to push a finger key in response to a light The slope for Hick's data is 11 sec per bit Even steeper slopes are found when finger responses must be made to numerals rather than to lights Hyman (1953) reported a slope of 18 sec per bit for such a task and the data of Brainard et al (1962) presented earlier also give 18 sec per bit Thus the slope of these last

[2] The term *set* as used in this paper has two meanings Cognitive set refers to preparation in advance for the probabilities or contingencies characterizing a given situation This meaning of the term set is similar to what Miller Galanter and Pribram (1960) call a Plan. The other usage of the word set is the mathematical one meaning a number of things of the same kind. Fortunately the two meanings are congruent.

functions are 10 times as steep as for the pointing responses shown in Fig 15

These data are subject to an interesting interpretation from the view

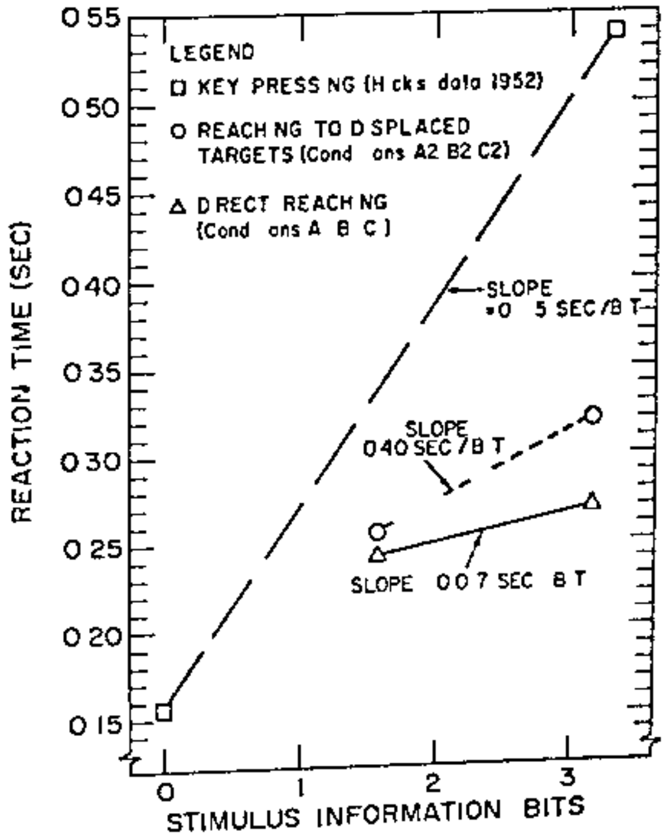

FIG 15 Effects of increasing stimulus uncertainty on choice reaction time for tasks having different levels of S–R compatibility The upper curve is from Hick (1952) for key pressing to lights the lower curves are data from Fitts & Peterson (in press) for highly compatible pointing responses to lights

point of learning theory As we progress from tasks low in compatibility to ones of relatively high compatibility, *S*s are presumably making more and more use of very well established habits (i e , using responses which show strong population stereotypes) It appears, therefore, that the effects of stimulus uncertainty gradually become less and less marked in magnitude as a result of continued practice in information handling tasks There is considerable evidence, not reviewed here, for this conclusion On the surface this empirical finding can easily be interpreted as supporting the notion of the learning of specific S–R associations However, other experiments, which will now be described, demonstrate that part of the effect is due to cognitive set learning (i e , learning which has to do with sets of stimuli or sets of responses)

Subset familiarity —In studies of learning in an information handling task as a function of stimulus uncertainty one is confronted with a problem very similar to that involved in attempting to construct different sets of materials equated for meaningfulness for use in a rote learning experiment This is the problem of controlling the amount of previous experience with alphabets, or S–R ensembles, of different size In some instances the stimulus side of the problem can be solved by using lights, pictures or other types of symbols which are drawn from sets of indeterminate maximum size Subsets of symbols such as numerals and letters, drawn from alphabets of a known and fixed size, however, are immediately suspect To put it simply, *S*s may continue to respond as if the entire alphabet were possible, even though the experimenter uses only a subset of the available symbols

Fitts and Switzer (1962) have recently demonstrated such effects in a series of three experiments In one experiment three sets of numerals and three groups of *S*s were used The task was very simple—to say the name of a numeral as soon as it was exposed One group worked with eight numerals, 1 through 8 A second group used an unfamiliar subset of two numerals, 2 and 7 A third group used a relatively familiar subset of two numerals, 1 and 2 Results, for three training sessions, are shown in Fig 16 Only the data for the numeral 2, which is common to all three groups, are shown On the first session vocal reaction time was the same for the numeral 2 when it was one of eight numerals and when it was a member of an unfamiliar subset of two numerals When the same numeral appeared as one of a familiar subset of two stimuli, however, reaction time was faster Not unexpectedly, learning was fastest for the small, unfamiliar subset Similar results were found in two other experiments with alphabetic symbols Figure 17 summarizes results for the three groups in this study which used, respectively, all 26 letters, an unfamiliar subset (EBP) and a familiar

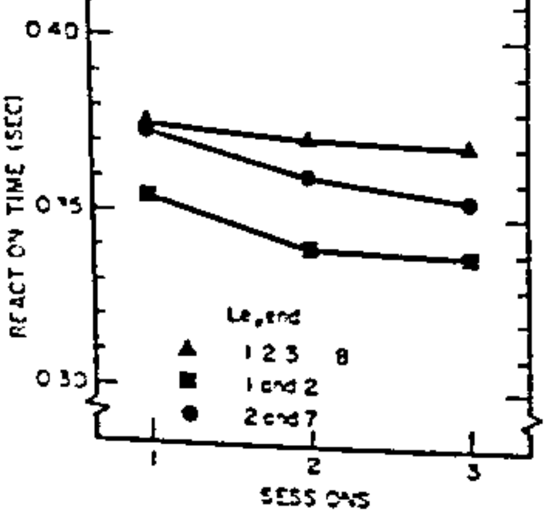

FIG 16 Choice reaction time in vocalizing the name of the numeral 2, as a function of the set of alternative numerals with which 2 is associated (after Fitts & Switzer 1962)

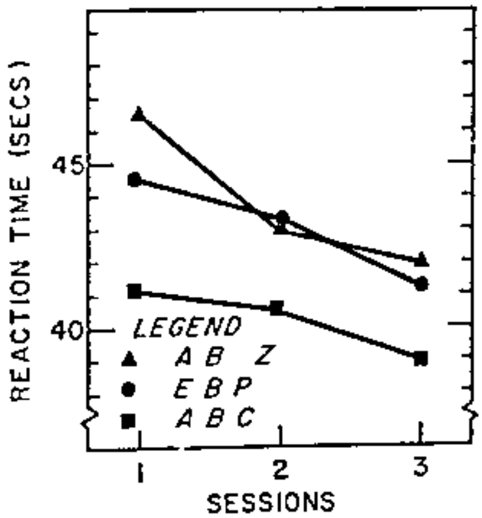

FIG 17 Choice reaction time in vocalizing the name of the letter B as a function of the set of alternative letters with which B is associated (after Fitts & Switzer, 1962)

subset (ABC) The data shown here are for the letter B which was common to all three sets The results are similar to those for the previous experiment and are significant statistically However, it should be noted that in all of these experiments the absolute differences are small, in agreement with the general finding for other highly compatible tasks

These results show clearly that even in the case of S–R associations that presumably have been practiced almost daily for at least fifteen years, cognitive sets are operating to some extent This offers support to the view that cognitive factors are important in all types of highly practiced skills The importance of cognitive set effects is further indicated by experiments with redundant sequences

Redundant sequences—We turn now to a topic which is at the heart of perceptual motor skill learning This is learning about sequences or patterns of events, where the patterns are probabilistic rather than deterministic

James McKeen Cattell (1886) was the first to study this problem from what is now called an informational point of view, working in this country and in Wundt's laboratory in Germany Cattell made up sequences of letters and of words which the *S*s (Cattell himself and such volunteers as G O Berger, John Dewey, and G Stanley Hall) read serially as rapidly as possible In some instances letter and word sequences were those of English sentences, in other instances letters and words from English text were printed in reverse order thus giving unfamiliar sequences Cattell found that " it takes about twice as long to read (aloud, as fast as possible) words which have no connexion as words which make sentences, and letters which have no connexion as letters which make words" (1886, p 64) He then verified these results with text taken from French, German, Italian, Latin, and Greek and found that the magnitude of the effect attributable to language structure was proportional to familiarity with the language Cattell's discrete vocal reaction times, incidentally, were of about the same absolute magnitude as those shown in Fig 17 (slightly less than 0 5 sec.).

Fitts, Wolpe, and Peterson (1963) have recently completed several studies in which they have measured discrete vocal reaction times to the elements of redundant sequences of numerals Holding the size of the set of numerals fixed at nine (1 through 9), one of the numerals was made more and more probable, all the remainder being made equally and increasingly less probable Maximum redundancy involved a sequence of 126 stimuli out of which 118 were the frequent symbol and each of the other eight symbols appeared only once (R = 87%). Reaction time data for different groups of *S*s are shown in Fig 18 All numerals were equally probable on Session 1; on the next three sessions each group worked at a different level of redundancy Differences in reaction times to frequent vs infrequent elements increased as a function of degree of redundancy. Unfortunately, as it turned out, the numeral 1, which was chosen as the most frequent numeral in the first experiment, gave slightly faster reaction times than the average for the remaining stimuli under the equal frequency

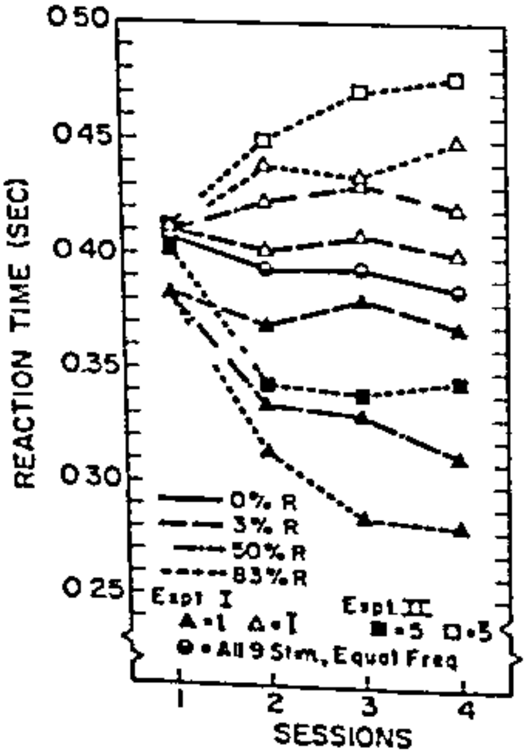

Fig 18 Differential choice reaction times in vocalizing the names of frequent and infrequent numerals as a function of increasing frequency unbalance (redundancy) (after Fitts, Peterson & Wolpe, 1963) In Exp 1 the numeral 1 was most frequent, in Exp 2 the numeral 5 was most frequent.

condition Therefore, one additional high redundancy group was run with the numeral 5 as the most frequent element The results for this group are very similar to those for the previous groups when the latter are corrected for the slight initial difference between 1's and other numerals These data, and some comparable results from a very different and much more compatible task are also shown in Fig 19 The difference in reaction times to infrequent vs frequent stimuli apparently increases linearly with redundancy, the slope of the function decreasing with degree of S–R compatibility

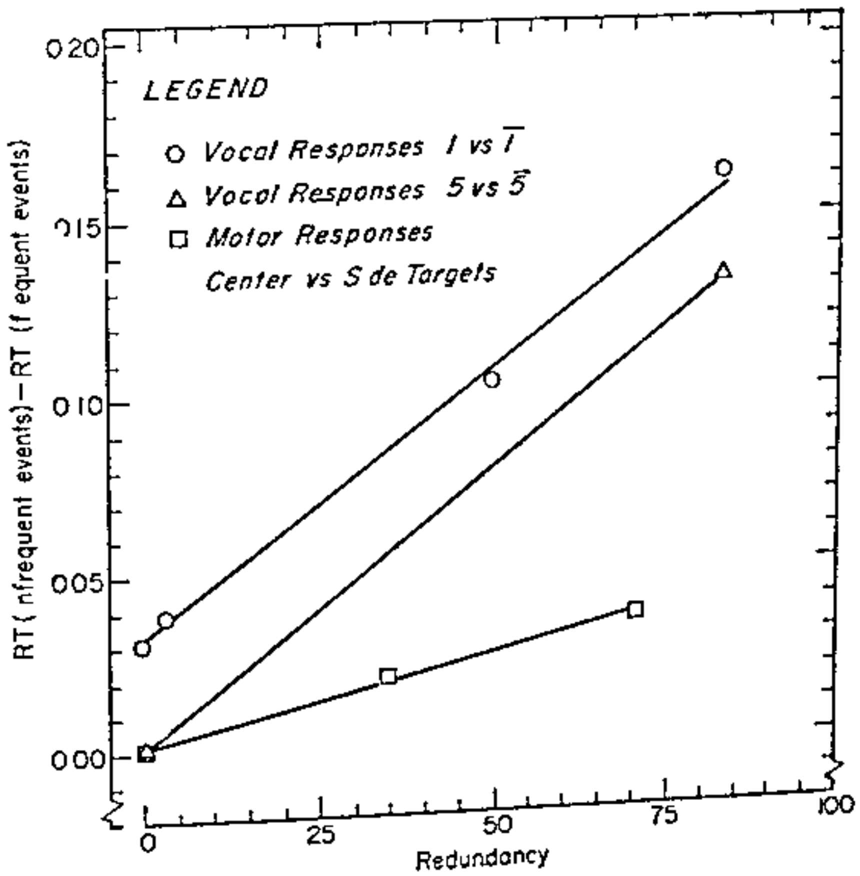

FIG 19 Differences in vocal reaction times to frequent vs infrequent elements of a set expressed as a function of the redundancy of the stimulus sequence The two top curves are for the last two sessions of the data shown in Fig 18 the bottom curve is for a task in which *S* had to make highly compatible pointing responses to lights (after Fitts Peterson & Wolpe 1963)

The error data from these reaction time experiments present another and highly important side of this picture Total errors remained highly stable at around 1% of all responses throughout the four sessions, but the proportions of errors made to the infrequent stimuli increased steadily relative to those made to the frequent stimuli

Space does not permit a full discussion of the theoretical significance of these error data, which can be interpreted in terms of a sequential stimulus sampling theory It is obvious, however, that speed and accuracy in responding to any particular stimulus element in a sequence is influenced markedly by the probabilities governing its occurrence in the sequence This general finding is, of course, an old and well known one However, the demonstration of the extent and lawfulness of the effect, in terms of stimulus redundancy, is new, and of considerable theoretical importance This finding is strongly suggestive of operations analogous to a sequential statistical decision process Stated simply, a sequential statistical decision model of an information handling process hypothesizes that a cognitive set is first established which assumes certain a priori probabilities or odds, in advance of the occurrence of the next stimulus During the subsequent reaction time new information, from successive stimulus samples, is used to modify these initial odds until the posterior odds become sufficiently large (or small) to warrant the risks involved in making a decision, at which time a response is initiated The fact that a computer can be programmed to make decisions in this manner, and that such a computer would show differential reaction times and make proportions of errors much like human *Ss* lends some degree of plausibility to the sequential stimulus sampling theory

The general conclusions reached in regard to cognitive set learning and skilled performance are as follows (*a*) cognitive sets develop very slowly, and tend to generalize over many classes of similar situations, (*b*) however, once established they can be "called up" in a matter of about a second or less by an appropriate cue, (*c*) elicitation and utilization of cognitive sets is often facilitated by the availability of verbal labels for use as cues although such labels are not necessary

The experiments discussed above involved discrete and serial vocal and motor responses It is assumed that similar phenomena can be found in many other perceptual motor tasks, such as a batter facing a pitcher who can throw a variety of pitches, and a pilot learning to handle an airplane in rough air In both of these examples stimulus probability learning is involved

Some Cross-Category Problems of Skill Learning

In the remainder of this paper the relevance of the general views regarding skilled performance and skill learning processes discussed up to this point will be considered as they apply to several additional and more specific topics Emphasis will be on the relation of skill learning to other learning tasks

Discrimination Capacity and Skill Learning

The first of these topics is the relation of sensory, perceptual, and short-term memory processes to skill learning. It is proposed that precision in controlling the amplitude and timing of a movement is limited by, and should never exceed, the capacity of an individual to learn to discriminate the external and proprioceptive feedback resulting from the single responses or series of responses. Supporting this conjecture is the fact that augmentation of feedback, in such a way as to increase discriminability, usually results in reliable increments in skilled performance and learning rate. This is true when the magnitude of display changes is increased so as to enhance the discriminability of visual cues, or when the elasticity or viscosity of a control is increased so as to enhance the discriminability of proprioceptive feedback. Bahrick (1957) has shown, for example, that addition of a spring to a control leads to improvement of blind positioning movements of that control—presumably because each increment in response amplitude now has associated with it a more easily discriminated change in force, resulting from displacement of the spring. Bahrick and Noble (1961) have recently obtained empirical gradients of response generalization, which they interpret as reflecting failure in discriminating among adjacent responses, i.e., response similarity effects, and have studied the effects of increasing stimulus vs. increasing response discriminability. They conclude that response similarity has a greater effect upon response generalization than does stimulus similarity in a task where different motor responses are made to a series of stimuli.

Where the same response, or a small set of responses, are made over and over again, it would appear, however, that the average timing and precision of responses may come to exceed the *S*'s ability to discriminate single stimuli, at least as discriminability is measured by standard psychophysical methods. Such evidence suggests that the *S* is able eventually to learn somehow to adjust his responses in accordance with the accumulated information gained from a series of discriminations, and to reduce his response variability below his error in judging single responses. In other words, at very high levels of practice in a highly coherent task, variability of response becomes less and response differentiation better, than would be predicted from ordinary psychophysical data taken early in learning. Perhaps this simply indicates a capacity for long continued discrimination and probability learning, similar to the demonstrated capacity for long continued improvement in the speed of performance. Another important fact to consider, however, is that the criterion for discrimination often is a 75% or even higher proportion of successes (in 2-choice tasks) whereas probability learning effects may continue to operate at levels only very slightly above chance, albeit over a very large number of responses

As an aside, at this point, learning theorists who place great emphasis on the role of response produced stimuli need to be reminded that discrimination of such stimuli is relatively poor if the judgment is on an absolute basis along a single dimension For example, *S*s identify a maximum of only about 2 bits of information in judging the pressure which they are applying to a control Again, this does not rule out the possibility of slow probability learning effects, however

The importance of stimulus discrimination learning varies, of course, with the nature of the overall task For example, proprioceptive discrimination should be most important in skills where there is little uncertainty regarding what response is appropriate and *S* is confronted with the task of precise response execution Learning to execute a complex dive would be an example

Short-Term Memory and Skill Learning

Several writers have discussed the role of short term running memory in the learning of perceptual motor skills Again we find in the early work of Cattell (1886) a suggestion of the effects of memory limitations on the speed of perceptual motor performance Cattell exposed letters which the *S* read as they passed behind a slit By varying the width of the slit *S*s were permitted to see one or more than one letter at a time—a condition called *preview* He found that ability to see more than one letter at a time increased serial reading speed up to a preview limit of four or five letters, but that the major advantage was gained as soon as the second letter was visible Wagoner and Fitts, in an unpublished study completed several years ago, found similar results for preview when the task was to push the appropriate one of five keys at exactly the time that light points, moving downward in five different columns, passed behind a horizontal line which extended across the five columns Most of the advantage gained from permitting preview was achieved by viewing the next light in the sequence A preview of 12 oncoming lights was little better than the preview of only one

Crossman (1960) has recently published a theoretical analysis of 'perceptual anticipation' in pursuit tracking as a function of a hypothetical limit on capacity for processing information, and a limit on capacity for running memory His main thesis is that one or the other of these capacities may determine the limit of performance in a given situation For example, when redundancy is high but the task is very complex there should be considerable gain from preview over several seconds or over a large number of forthcoming stimuli, memory capacity presumably would be the limiting factor in this situation.

Continuous and serial tasks often provide an opportunity for measuring the lag, and hence the memory load, between the information-seeking responses of the eye, and the output responses of the hand or vocal mechanism. Studies of eye-hand span in typing, playing the piano, and assembly work, studies of eye voice span in oral reading, and studies of lag in copying telegraph code all indicate that closely comparable and near maximum amounts of information are carried in running memory in different perceptual-motor tasks.

Such limitations as these become especially important when we turn to the mechanisms which may account for continued improvement in highly coherent, speed skills at advanced levels of practice. These will be considered next.

Continued Improvement in Skills

Crossman (1959) is the only worker who has addressed himself specifically to the development of a theory regarding how continued improvement comes about at very high levels of skill and why improvement continues so slowly over so long a period of time.

Crossman assumes a general probability learning model. Thus he states that "the operator can be imagined to possess a repertoire or stock of *r* different methods, from which he picks one by chance for each cycle" (1959, p. 159). Each method has an initial probability, and these probabilities are modified after each (discrete) response as a function of feedback. However, since all responses at high levels of skill are "successful" in the ordinary sense that they all permit attainment of the objective, a critical problem is to account for the mechanism by means of which the time required for specific responses is discriminated with the degree of precision required by the selective process. One interesting hypothesis, among several advanced by Crossman, is a mechanism based on the rapid initial decay of short-term memory. Feedback from faster responses is hypothesized to arrive after less decay of the memory process than does feedback from slower responses and thus on the average should provide a positive increment in probability of the subsequent use of the faster response. Here again, it is important to remember that the selective process operates over very long periods of time, and hence may be able to use relatively unreliable or "noisy" feedback information.

Another source of evidence regarding long term skill learning mentioned briefly in an earlier section, concerns the ability of *Ss* to learn to carry on more than one task simultaneously. Bahrick, Noble, and Fitts (1954) reasoned that if proprioceptive feedback does become increasingly important after extended learning in highly coherent tasks, and if less and less reliance on visual cues is necessary as learning of a first task progresses, then a second visual task should have less and less interfering effects on the first task to the extent that the first task is (*a*) highly coherent, and (*b*) highly overpracticed. Both ideas were verified by experiments. These studies also provided unequivocal evidence that learning had been going on long after the original criterion employed in measuring learning on the first task had ceased to indicate evidence of improvement.

Feedback Variables in Skill Learning

Bilodeau and Bilodeau, in their recent review of motor-skills learning, conclude that "studies of feedback or knowledge of results show it to be the strongest, most important variable controlling performance and learning" (1961, p. 250), and provide a comprehensive review of the effects of this variable. In spite of its obvious importance, I shall not have much to say about the topic of feedback, however, partly because the evidence is so clear, and partly because, from a theoretical standpoint, there appears to be little in this area that is peculiar to skill learning as distinct from other learning tasks.

One interesting line of work on feedback should be mentioned, however. This is the effect of augmented feedback, the availability of special feedback information which ordinarily is not present in a skill learning task. Some of the effects of augmented feedback appear to be motivational. Fitts and Leonard (1957), for example, found that a continuous series of clicks at the rate of 2 per sec. heightened performance in a speeded perceptual task. Subsequent studies (Smode, 1958, Kinkade, 1960) suggest the possibility of additional learning effects as well as performance effects.

One of the avenues by means of which augmented feedback may influence skill learning is through its effect on discrimination learning, especially during advanced stages of practice. When the task is a relatively incoherent one, augmented feedback may also provide much more reliable information than is ordinarily available to the *S* as regards the adequacy of his general strategy or cognitive set. In other words, as learning approaches the hypothetical limit of the *S*'s ability to discriminate available feedback, in either coherent or incoherent tasks, augmented feedback may become increasingly useful because of the more precise information it provides to the learner.

Skill Learning and Problem Solving

Several writers have recently emphasized the analogy between thinking and skill learning. At first these two forms of behavior may seem to be at opposite ends of a continuum However, the approach to skilled performance developed in the present paper, especially the emphasis on the patterning and organization of skills and on the importance of cognitive set phenomena, make the relationship more plausible Bartlett (1958) stressed the idea that the extrapolation and orderly sequencing of responses is involved in both skilled performance and in thinking In a similar vein Piaget (1950) proposed that "intelligence sensori motoric" precedes and provides the foundation for "intelligence intellectualle"

Certainly the role of cognitive set in skilled performance, and the general adaptive system model of skilled performance, with its emphasis on hierarchical programs, brings skilled and problem solving behavior closer together than would have been commonly proposed a few years ago Perhaps there the matter should rest until additional evidence regarding the relationship is at hand

Some Relatively Unique Aspects of Skill Learning

Lest the similarity of skill learning to other learning tasks be overemphasized, I shall close this paper with brief mention of four areas that are relatively unique to, but very important for, the study of skilled processes These topics will not be discussed at length because they are judged to be of somewhat peripheral interest to those working in other areas of human learning

Open-loop behavior at various stages of learning —For various theoretical reasons it would be especially instructive to study perceptual motor performance in continuous or serial tasks where either the feedback which *S* normally expects and uses or the input which is mixed with feedback, is temporarily eliminated so that *S* would respond to one of these sources of information alone For example this would permit a determination of the relative importance of input vs feedback, and of the degree to which response-generated information (feedback) is sufficient to maintain performance In the area of skills this is called the study of "open loop" responses It is an easy matter to eliminate visual or auditory feedback in most perceptual-motor tasks (such as by having subjects close their eyes), but the elimination of proprioceptive feedback is usually not possible, and as long as the latter is present *S* quickly realizes that he is no longer getting exteroceptive feedback and usually changes his behavior accordingly Some success has been met in eliminating the input and arranging the task so that *S* responds only to his own feedback However it is difficult to do this without the *S* realizing that the input has suddenly stopped Thus the separate effects of input vs feedback are only partly understood

Analysis of complex forms of stimulus response congruence —Some of the highest levels of skill are attained in tasks in which one movement pattern is superimposed upon another pattern, such as in aiming a gun at a moving target while at the same time maintaining an upright posture while standing on a moving platform, or in throwing a football at a moving target while running at full speed. Performance in such tasks would appear to exceed ordinary human information processing capacity and must therefore depend on the use of highly overlearned or automatized subroutines. It would be highly instructive to study such learning but little work has been done on this problem, perhaps because of the technical difficulties involved in recording and analyzing separately two concurrent response processes.

Speed-accuracy tradeoff.—Man has the rather unique ability to exchange speed for accuracy of responses and vice versa. High levels of ability in effecting such compromises are evidenced in almost all information handling and control tasks, suggesting a basic interdependence between mechanisms for the regulation of timing and mechanisms for the regulation of the direction and amplitude of movement. The sequential stimulus sampling theory described previously is one example of an effort to understand these interrelations. A recent study by Fitts and Peterson (1964) provides clear evidence that the speed accuracy relation is determined by motor centers which are quite separate from those involved in the control of choice reaction time, since movement time and reaction time were found to be quite independent functions.

Human transfer functions.—A small but active group of researchers have for the past ten years been interested in analyzing and constructing mathematical models of the processes by means of which a man learns to control the output of a complex dynamic system, such as one in which the output is the second or third integral of the input. This is a problem unique to the study of skill learning (Licklider, 1960). The topic is a highly interesting one because, as mentioned earlier, the same theory which has been developed for the analysis and synthesis of dynamic physical systems can, to a considerable extent, be applied directly to the description of human perceptual motor learning and performance. Theory of sampled-data systems is especially relevant to current work in this area.

SUMMARY

In this chapter I have placed particular emphasis upon (*a*) the importance of research on spatial temporal patterns of behavior, including patterns lasting for only a second or less, and (*b*) the importance of stimulus coherence as the objective characteristic of tasks and sequences which appears to be of widest importance and of most theoretical interest.

The theoretical idea which I would re-emphasize is that of hierarchical processes One useful way to view the higher level processes in a complex skill is by analogy with the executive routines written into computer programs The corresponding view of lower level processes is by analogy to the loops and subroutines of such programs The theoretical view of skilled performance here proposed minimizes the role of motor behavior per se, and thus removes the principal basis for the commonly made distinction between verbal and motor processes Instead it places major emphasis on the intrinsic coherence of stimulus and response sequences and the cognitive or higher-level processes that govern behavior sequence, and suggests that important aspects of response sequences include such factors as timing, the interrelations of speed, accuracy, and uncertainty, and the limitations imposed by capacities for discrimination and memory

The crucial point in developing a general theory of skilled performance, and in support of the view that verbal and motor processes are highly similar, is the conclusion that skilled performance is dependent on discrete or quantized processes Thus the study of discrete perceptual motor responses, including the study of reaction time, movement time, and response accuracy (errors), can be viewed as contributing to an understanding of serial and continuous communication and control skills on the one hand and to an understanding of the organization of thinking decision making, and verbal behavior on the other hand

References

ALLUISI E A Conditions affecting the amount of information in absolute judgments *Psychol Rev* 1957 64 97–103

BAHRICK, H P An analysis of stimulus variables influencing the proprioceptive control of movement *Psychol Rev* 1957 64 324–328

BAHRICK H P NOBLE M E & FITTS P M Extra task performance as a measure of learning a primary task *J exp Psychol* 1954 48, 292–302

BAHRICK H P & NOBLE M On stimulus and response discriminability *J exp Psychol* 1961 61, 449–454

BARTLETT F C *Thinking* London Allen & Unwin 1958

BILODEAU E A & BILODEAU I McD Motor skills learning *Annu Rev Psychol* 1961 12, 243–280

BLACKBURN J M Acquisition of skill an analysis of learning curves Great Britain I H R B Report No 73 1936

BRAINARD R W IRBY T S FITTS P M & ALLUISI E A Some variables influencing the rate of gain of information *J exp Psychol* 1962 63 105–110

BRYAN W L & HARTER N Studies on the telegraphic language The acquisition of a hierarchy of habits *Psychol Rev* 1899 6, 345–375

CATTELL J McK The inertia of the eye and brain *Brain* 1885 8, 295–312

CATTELL, J McK The time it takes to see and name objects *Mind* 1886 11, 63–65

CRAIK K J W Theory of the human operator in control systems II Man as an element in a control system *Brit J Psychol* 1948 38, 142–148

CROSSMAN, E R F W A theory of the acquisition of speed skill *Ergonomics*, 1959, 2, 153–166

CROSSMAN, E R F W The information capacity of the human motor system in pursuit tracking *Quart J exp Psychol*, 1960, 12, 1–16

FITTS, P M The information capacity of the human motor system in controlling the amplitude of movement. *J exp Psychol*, 1954, 47, 381–391

FITTS P M Skill training In R. Glaser (Ed), *Training research and education* Pittsburgh Univer Pittsburgh Press 1962

FITTS P M, BAHRICK, H P, NOBLE, M E, & BRIGGS, G E *Skilled performance* New York Wiley in press

FITTS P M, BENNETT, W E., & BAHRICK, H P Application of autocorrelation and cross-correlation analysis to the study of tracking behavior In G Finch and F Cameron (Ed), *Air Force human engineering personnel and training research* Washington National Academy of Sciences—National Research Council Publ 455, 1956 pp 125–141

FITTS P M., & DEININGER R. L S–R compatibility Correspondence among paired elements within stimulus and response codes *J exp Psychol*, 1954, 48, 483–492

FITTS P M, & LEONARD J A Stimulus correlates of visual pattern recognition—a probability approach. Final report Contract No NONR-495(02) Columbus Ohio Ohio State University Research Foundation Oct., 1957

FITTS, P M., & PETERSON J R The information capacity of discrete motor responses *J exp Psychol*, 1964, in press

FITTS P M., PETERSON, J R. & WOLPE, G Cognitive aspects of information processing II Adjustments to stimulus redundancy *J exp Psychol*, 1963, 65, 423–432

FITTS P M, & SEEGER, C M S–R compatibility Spatial characteristics of stimulus and response codes *J exp Psychol*, 1953, 46, 199–210

FITTS P M, & SWITZER, GAIL. Cognitive aspects of information processing I. The familiarity of S–R sets and subsets *J exp Psychol* 1962 63, 321–329

FLEISHMAN E. A., & HEMPEL, W E Changes in factor structure of a complex psychomotor task as a function of practice *Psychometrika* 1954, 19, 239–252

FLEISHMAN, E A, & HEMPEL, W E. Relation between abilities and improvement with practice in a visual discrimination reaction task. *J exp Psychol*, 1955 49, 301–312

FULLERTON G S., & CATTELL, J McK. *On the perception of small differences, with special reference to the extent, force, and time of movement* Philadelphia Univer Pennsylvania Press, Philosophical Series No 2, 1892

GIBSON J E Making sense out of the adaptive principle *Control Engng*, 1960, 7, 113–119

GREW S Information gain in tasks involving different stimulus-response relationships *Nature*, 1958 182, 1819

HICK, W E. Discontinuous functioning of the human operator in pursuit tasks. *Quart J exp Psychol* 1948 1, 36-57

HICK, W E. On the rate of gain of information. Quart. *J exp Psychol.*, 1952, 4, 11–26

HIRSH I J & SHERRICK C E. Perceived order in different sense modalities *J exp Psychol*, 1961 62, 423–432.

HYMAN R. Stimulus information as a determinant of reaction time. *J exp Psychol.*, 1953 45, 188–196

KELLER, F S The phantom plateau *J exp Anal Behav*, 1958, 1, 1–13

KINKADE, R G The effect of augmented feedback on the acquisition and transfer of a tracking skill Unpublished Ph D thesis, Ohio State Univer, 1960

KLEMMER, E T Communication and human performance *Human Factors J*, 1962, 4, 75–79

LASHLEY, K S The problem of serial order in behavior In L A Jeffress (Ed), *Cerebral mechanisms in behavior* New York Wiley, 1951

LICKLIDER, J C R Quasi linear operator models in the study of manual tracking In R D Luce (Ed), *Developments in mathematical psychology* Glencoe, Illinois Free Press, 1960

MILLER, G A The magical number seven plus or minus two Some limits on our capacity for processing information *Psychol Rev*, 1956, 63, 81–97

MILLER, G A, GALANTER, E, & PRIBRAM, K H *Plans and the structure of behavior* New York Holt, 1960

MONTPELLIER, G de Note sur l'acceleration dans les mouvements volontaires de la main *Arch Psychol, Geneve*, 1937, 26, 181–197

NEWELL, A, SHAW, J C, & SIMON, H A Elements of a theory of human problem solving *Psychol Rev*, 1958, 65, 151–166

NEWMAN, E B Men and information A psychologist's view N 2 del Supplemento del Neuovo Cimento, 1959, 13, 539–559

NOBLE, M E, FITTS, P M, & WARREN, C E The frequency response of skilled subjects in a pursuit tracking task *J exp Psychol*, 1955, 49, 249–256

PIAGET, J *Psychologie de l intelligence* New York Harcourt, Brace, 1950

PIERCE, J R, & KARLIN, J E Reading rates and the information rate of a human channel *Bell Syst tech J*, 1957, 36, 497–516

RIESEN, A H, & AARONS LOUISE Visual movement and intensity discrimination in cats after early deprivation of pattern vision *J comp physiol Psychol*, 1959, 52, 142–149

RUHLE, W, & SMITH, K U Effects of inversion of the visual field on human motions *J exp Psychol*, 1959, 57, 338–343

SMODE, A Learning and performance in a tracking task under two levels of achievement information feedback *J exp Psychol*, 1958, 56, 297–304

SNODDY, G S Learning and stability *J appl Psychol*, 1926, 10, 1–36

SNYDER, F W, & PRONKO, H H *Vision with spatial inversion* Wichita, Kansas Univer of Wichita Press, 1952

STETSON, R H A motor theory of rhythm and discrete succession *Psychol Rev*, 1905, 12, 250–370

TAYLOR, F V Psychology and the design of machines *Amer Psychologist*, 1957, 12, 249–258

TROLAND, L T *The fundamentals of human motivation* New York Van Nostrand, 1928

UNDERWOOD, B J, & SCHULZ, R W *Meaningfulness and verbal learning* New York Lippincott, 1960

WELFORD, A T The psychological refractory period and the timing of high speed performance—A review and a theory *Brit J Psychol* 1952, 43, 2–19

WOODWORTH, R S The accuracy of voluntary movement. *Psychol Rev Monogr Suppl*, 1899, Whole No 13

WOODWORTH, R S *Dynamics of behavior* New York Holt, 1958