AD-A012 097

HUMAN PERCEPTUAL-MOTOR PERFORMANCE

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Prepared for

Air Force Office of Scientific Research
Advanced Research Projects Agency
National Aeronautics and Space Administration

August 1974

HUMAN PERFORMANCE CENTER

DEPARTMENT OF PSYCHOLOGY

The University of Michigan, Ann Arbor

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Technical Report No. 48

August 1974

THE HUMAN PERFORMANCE CENTER

DEPARTMENT OF PSYCHOLOGY

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER AFOSR - TR - 75 - 0907	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) Human Perceptual-Motor Performance		5. TYPE OF REPORT & PERIOD COVERED Technical Report Interim
		6. PERFORMING ORG. REPORT NUMBER Technical Report No. 48
7. AUTHOR(s) Richard W. Pew		8. CONTRACT OR GRANT NUMBER(s) F44620-72-C-0019
9. PERFORMING ORGANIZATION NAME AND ADDRESS Human Performance Center 330 Packard Road Ann Arbor, Michigan 48104		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 61101D/1949/681313
11. CONTROLLING OFFICE NAME AND ADDRESS Advanced Research Projects Agency 1400 Wilson Blvd. Arlington, Va. 22209		12. REPORT DATE Aug. 1974
		13. NUMBER OF PAGES 83
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office) Air Force Office of Scientific Research/NL 1400 Wilson Blvd. Arlington, Va. 22209		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

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

18. SUPPLEMENTARY NOTES

PRICES SUBJECT TO CHANGE

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

human controller performance
human feedback control
human information processing
human motor control
human movement control
human tracking performance
motor program
perceptual-motor performance

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

The paper presents a tutorial review of the current status of work on perceptual motor skills from the joint perspectives of information processing and feedback control. The organizing theme for the discussion is a multi-level conception of motor control encorporating (1) an elementary error-correction system; (2) higher level feedback and control functions describing how man responds to the predictable characteristics of input signals and (3) a schema based memory and response execution system for

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describing voluntary movement capacities. Elementary concepts of feedback control are introduced together with discussion of the role of feedback on performance, in tracking and in voluntary movement.

Human Perceptual-Motor Performance[1]

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Prologue

It is fitting for two reasons that the first chapter of this book about human information processing be concerned with perceptual-motor performance. First, it is only in recent years that motor performance has begun again to be dealt with as process (Keele, 1973) in contrast with the task-oriented analyses that have dominated the post-World War II period (Poulton, 1966) or the learning theory approach that emerged in the 1930's and continues to have its vocal advocates (see, for example, Bilodeau, 1966). Motor performance has been the laggard in this respect. Process-oriented views of perception, memory, and decision are already well-advanced (Neisser, 1967; Broadbent, 1971). The difficulty is documented in Welford's encyclopedic work on skills (Welford, 1968). A glance at Professor Welford's chapter headings clearly confirms his belief in an information-processing orientation to skills; however, the one chapter in which his retreat to a descriptive level is particularly noticeable is the chapter on movement.

Second, it is very difficult to discuss perceptual motor performance without embracing the entire domain of human information processing. Inferences about processing acquired by examining time delays in following a target course are closely related to the inferences derived from measurement of discrete reaction times (Pachella, Chapter 2). Producing a movement pattern that varies in space and time presupposes the capability to organize other classes of events serially (Jones, Chapter 5), and a hierarchical structure appropriate to the synthesis of motor skills surely must draw on such structures as they are revealed in intellectual tasks (Hunt, Chapter 7). While this chapter will make contact with topics discussed in virtually all the other chapters in this book, the subject matter and perspective are necessarily different. In this sense it should at once introduce the diversity of information-processing activities while it also communicates the unique subject matter of motor performance: movement control, utilization of response-produced feedback, and the organization and patterning of behavior in time.

Overview of What is to Come. There is no theory that encompasses all we want to know about motor performance. A myriad of processes and mechanisms act in concert to make possible the exquisite control and organization, the sheer grace and beauty, that typify the performance of the skilled athlete, musician, or experienced industrial worker.

This chapter will deal with three levels at which this control and organization are manifest. At the lowest level an individual brings to bear on any skilled task a rudimentary servomechanism, a system that permits the generation of a stream of simple motor outputs that is responsive to perceived differences between a desired state and an actual state. At the simplest level, with an unpredictable environment, this system, which is representable in terms of elementary concepts drawn from the theory of feedback control, acts point by point in time, contingent on changes in the environment and on the results of immediately preceding movements. It provides the basis, both conceptually and practically, for all higher levels of organization and programming. When prediction and programming fail to produce the desired performance, the servosystem takes up the slack and provides appropriate corrective signals. Successively higher levels of organization construct more integrated streams of motor commands, which are then executed and corrected by elements of the lower-level feedback control system. The chapter will begin with an introduction to the properties and performance of this rather mechanistic and "simple-minded" error-correction system.

If error correction were the limit of capability of the human motor system, as it is in lower organisms (e.g., the tropisms of single-celled animals), our performance would be crude and inadequate. At the next level to be explored in this chapter we must deal with an individual's capacity to act on the basis of the coherence and predictability of the environment with which he is interacting. At this level the performance is still highly stimulus bound, but the actor is capable of superseding the elementary control loop to generate more complex patterned outputs and to monitor the correspondence between the generated pattern and the desired pattern, by using more sophisticated error-detection mechanisms. In this section we must consider an individual's capacity to track predictable signals and to produce response sequences that take account of the dynamic responsiveness of the limb or external system being controlled. Even if the stimulus pattern to be followed is the same, the motor command stream appropriate to driving a sports car is not the same as that appropriate to a cross-country bus.

Finally, the full richness of human skilled performance depends on capacities not captured by strict stimulus-bound representations derived largely from the study of tracking tasks. Instead it is embodied in the ability to draw from the environment the appropriate initial conditions and to call up from memory integrated patterns of movement consonant with a desired goal. The third level of organization to be considered deals with the production of these self-initiated movements. It is at this level that our understanding and models are most incomplete.

It is clear that this division into three levels is at best a pedagogical convenience. The reader should think of motor control in terms of a hierarchically organized system in which the distinction among levels is diffuse and in which there is a rich interplay among the various processes that the individual calls upon to complete a given task. The relative importance of each depends on the environmental constraints, the criteria with respect to which performance is to be optimized, and the level of experience the performer brings to that activity.

Inner Loop Control

Minimizing Residual Motor Noise. Consider the task described by the block diagram of Fig. 1. The subject manipulates a rigidly-mounted control stick that produces an electrical output directly proportional to the force applied to it. He watches a display of his own output in comparison to a reference line that indicates the fixed magnitude of force he is requested to produce. The scale of the display is greatly magnified so that his most minute deviations from the desired force are presented to him. His task is to hold the prescribed force as accurately as he can. These conditions are designed to bring out the best a subject can do. He has only to correct for his own errors, and the display conditions make it easy for him to see them. In fact, in unpublished studies conducted by J. K. Thomas and myself, the average absolute error under these conditions (that is, the average deviation from the desired force

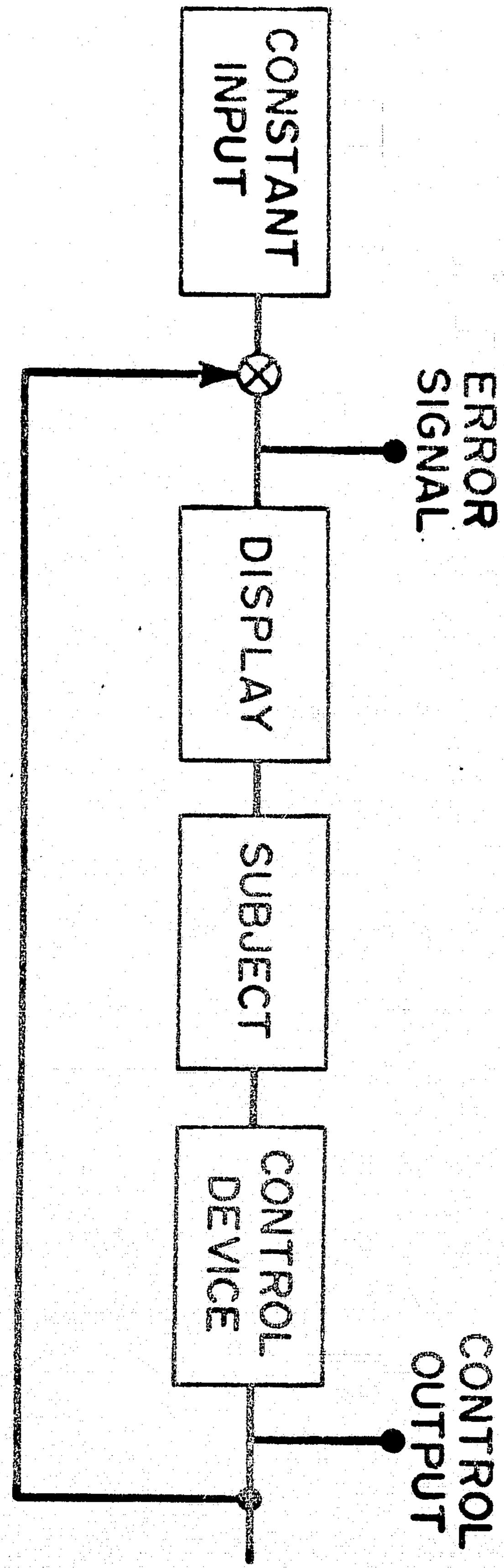

Fig. 1. Block diagram of the task of maintaining a constant force with visual feedback.

when the sign of the error is disregarded) was of the order of 1.4 gm (.0031 lb) when the commanded force was 454 gm (1 lb). With a 1400 gm commanded force, the average absolute error increased to 4.2 gm. We interpret this residual noise level in the output as a fundamental limitation in human motor control. A signal to noise ratio of 50 dB is about as good as he can do; the magnitude of the error scales multiplicatively with the magnitude of the applied force.

It is also instructive to examine the temporal properties of this residual motor noise. Since the error signal fluctuates randomly as a function of time, the appropriate way to capture its character is to compute its power spectrum, the average power or energy in the signal at each frequency, just as one would perform a frequency analysis of the noise produced by a jet aircraft or a motorcycle.[2]

The results of such an analysis are shown in Fig. 5 on page 20. The spectrum for the "no delay" condition closely approximates the spectra obtained in the Thomas and Pew force-holding experiment, although in the case of the spectrum shown in Fig. 5, a sinusoidal input signal having a frequency of 0.1 Hz (once cycle every ten seconds) was actually used instead of a constant input. Virtually all the power in human motor output is concentrated at frequencies below 15 Hz. There is a relatively sharp peak in the spectrum at approximately 10 Hz, which may be identified with normal psysiological tremor. Then there is a much broader peak that extends roughly from 0.5 Hz to 3.0 Hz that may be associated with the subject's attempts to correct for his own minute errors and the inevitable drift in produced force that results from trying to sustain an output force level.

In order to grasp the meaning of this spectral peak, suppose that the subject made corrections discretely and that the smallest time between responses were 200 msec. If, for tutorial puposes, we also suppose that corrections were made alternately to the left and right at the maximum rate possible, the subject would generate a waveform that completed one cycle of left and right alternations in 400 msec. If we analyzed the frequency of this waveform we would find that one cycle every 400 msec corresponds to 2.5 cycles per second (Hz). Under the assumption of discrete corrections, the implication here is that 3 Hz corresponds to a minimal time between changes in applied force of approximately 160 msec, a figure that is not unreasonable in light of simple reaction-time data. Similarly, the peak extending down to roughly 0.5 Hz implies that sometimes intervals as long as one second elapse between corrections. The analogy between discrete correction intervals and frequency should not be taken too literally; however, the intuitions implied by it are an appropriate way to interpret the frequency variable.

The subject in this experiment is being asked to perform a task that could easily be undertaken by an automatic system. Maintaining a constant level of a signal in the face of disturbances is called technically the <u>regulator problem</u>, and systems that are nothing more than refined versions of a thermostatically-controlled home heating system can be designed to solve the regulator problem to virtually any level of accuracy desired.

A regulator is conceptually the simplest form of feedback control system. It consists of an error detector and a controller. The error detector senses the difference between the desired state and the actual state of the system, which, of course, implies that knowledge of the actual state is available through feedback from the output. The controller provides command signals to drive the device being controlled, whether it is a furnace or simply a control stick. The controller may vary widely in the complexities of its dynamic characteristics. If we were to use a regulator system as a model for our subject who is attempting to maintain constant force output, it would have to incorporate nothing more than a gain or sensitivity factor appropriate to reproduce the signal to noise levels we observed and an effective time delay reflecting the subject's processing delays. In short, a model for the performance of a human subject in this simple task requires postulating nothing more complicated than a regulator and implies little in the way of cognitive control functions.

Tracking Random Signals. It is a conceptually simple step to generalize the task required of our subject by relaxing the constraint on the force level to be maintained and permitting it to vary over time in an unpredictable manner. Unpredictable signals are specified statistically, since their waveforms are never the same from trial to trial. The most important aspect of the signal that affects the accuracy with which a human subject can track is the signal's bandwidth. The technical definition of bandwidth refers to the range from lowest to highest frequency present in the signal. A hi-fi amplifier is said to transmit a band from 25 to 20,000 Hz. In the signals with which we deal, the low frequency is fixed and extends rather close to zero frequency, and we vary the high frequency cut-off. This has the effect of varying the rate of change or oscillation frequency of the signal from very slow (narrow bandwidth) to rather fast (wide bandwidth). As you will see from Fig. 2, an unpredictable signal having a bandwidth as wide as 1 Hz is very difficult for a human subject to follows. This figure presents the mean square error produced by a subject when he was attempting to track signals of different bandwidths (Elkind, 1956). The signals were random-appearing and had well-defined bandwidths. There was no power in the signal above the frequency F_{co}, but all frequencies below F_{co} were equally represented. The figure shows performance for both pursuit and compensatory displays. The compensatory display is of greatest interest at this point in the discussion. With such a display the subject sees only the error signal. He must move his control stick so as to return a cursor to the center of the display and thereby correct for any deviations introduced by the input signal. The output is literally subtracted from the input before it is presented to the subject, as is indicated by the circle with an X in it in Fig. 1. With a pursuit display, the subject is presented with a moving target corresponding to the pattern of the input and a moving cursor superimposed on the target as well as he can. I will return to a discussion of the implications of pursuit displays in a later section.

As can be seen from the curve for compensatory tracking in Fig. 2, the amount of tracking error rises slowly up to a bandwidth of approximately 0.6 Hz and then begins rapidly until above a bandwidth of 1.2 Hz the subject would be better off to leave the control stick at rest since he is creating more error than he is eliminating.

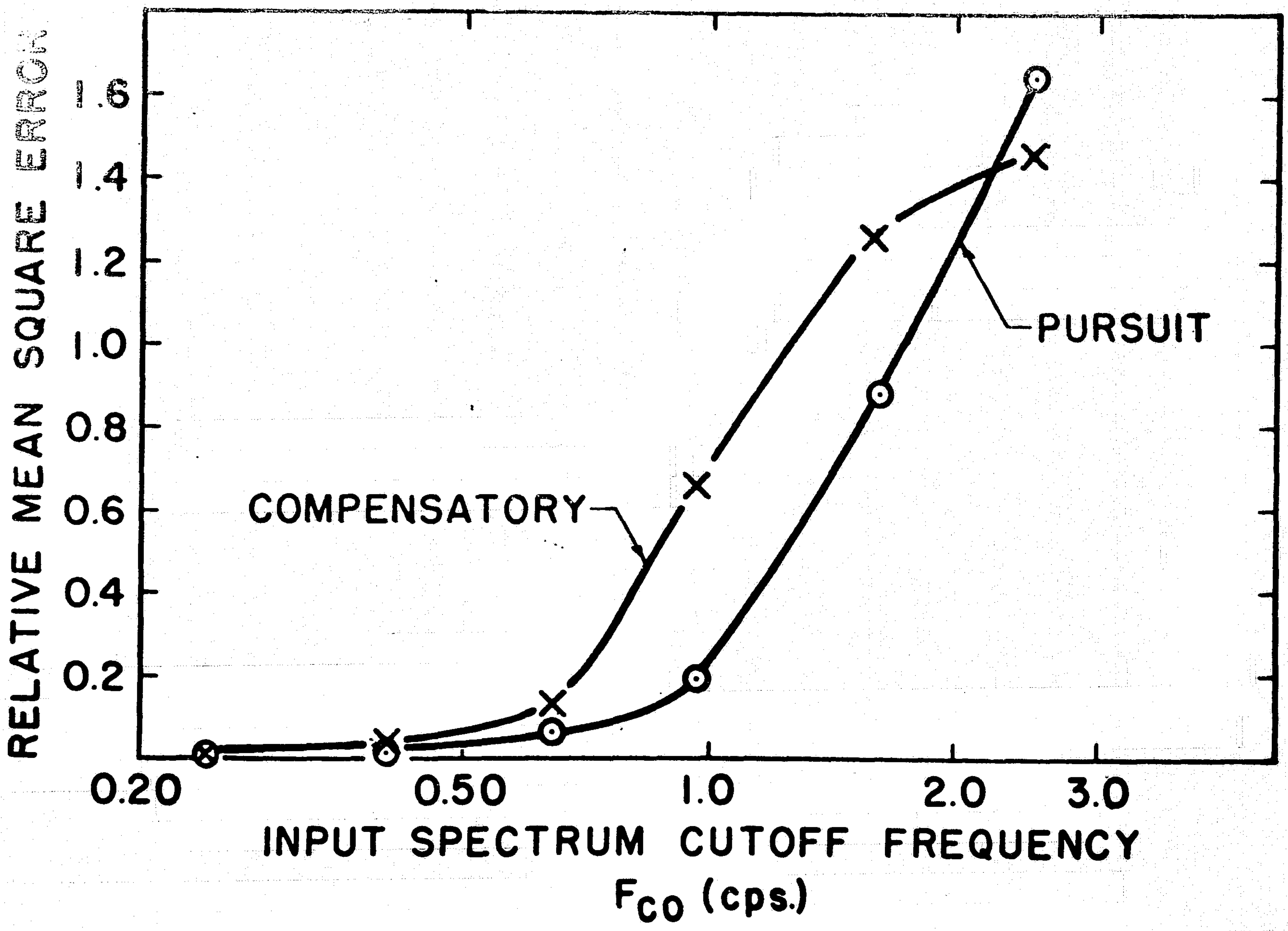

Fig. 2. Relative mean square tracking error as a function of the bandwidth of the random signal having an ideal rectangular spectrum with cutoff-frequency F_{CO}. The error score is computed as the ratio of mean square error relative to mean square input amplitude. Both pursuit and compensatory performance are shown (data from Elkind, 1956).

A Simple Model of Compensatory Tracking. Let us consider in detail the block diagram of a feedback model of a subject performing the task of compensatory tracking of a random signal as shown in Fig. 3. This description takes the model of Lemay and Westcott (1962) (see also Wilde & Westcott, 1963) as its referent because, conceptually, it is an easy model to understand and because it embodies the principle components needed to represent the subject's behavior.

The model assumes that the subject operates on a discrete time base, executing one movement every 200 msec. Beginning with the output end of the system, the Motor Command Generator and Muscle Mechanism act together to produce a "ballistic" movement every 200 msec. The input to this motor system is a desired change in the position of the limb. As shown in Fig. 4, the Motor Command Generator produces a pair of equal and opposite pulses of acceleration, each 100 msec in duration, the two together comprising the command for a simple movement. The amplitude of these pulses, and thereby the amplitude of the movement, is the only thing that is allowed to vary. These pulses are then transmitted to the Muscle Mechanism, which integrates them twice to produce a smooth change in position at its output, as shown also in the responses of Fig. 4. This representation of the muscle and limb system is a crude simplification that treats them together as a simple mass to which the accelerating forces are applied and neglects the physiological details of exactly how the muscles act to generate forces that move the limb. It is important to remember that all movements produced by this system take the same 200-msec to execute. Only the size of the movement may be changed on the basis of information received from earlier elements in the system.

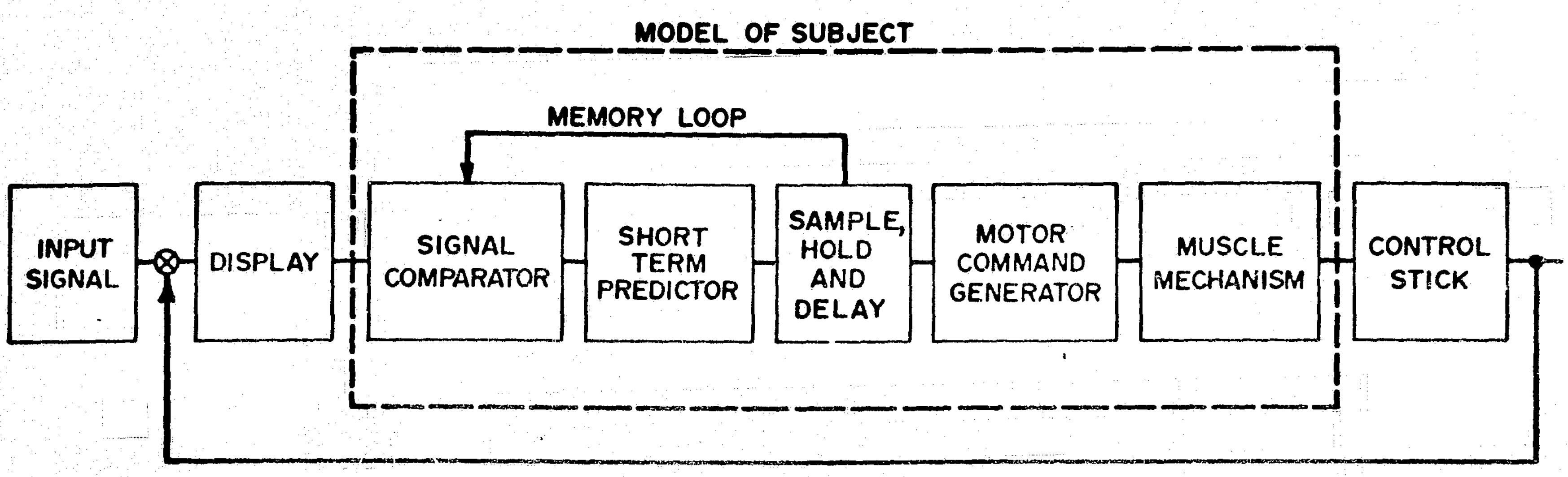

Fig. 3. Block diagram of feedback model for a subject performing a compensatory tracking task (based on the model of Lemay & Westcott, 1962).

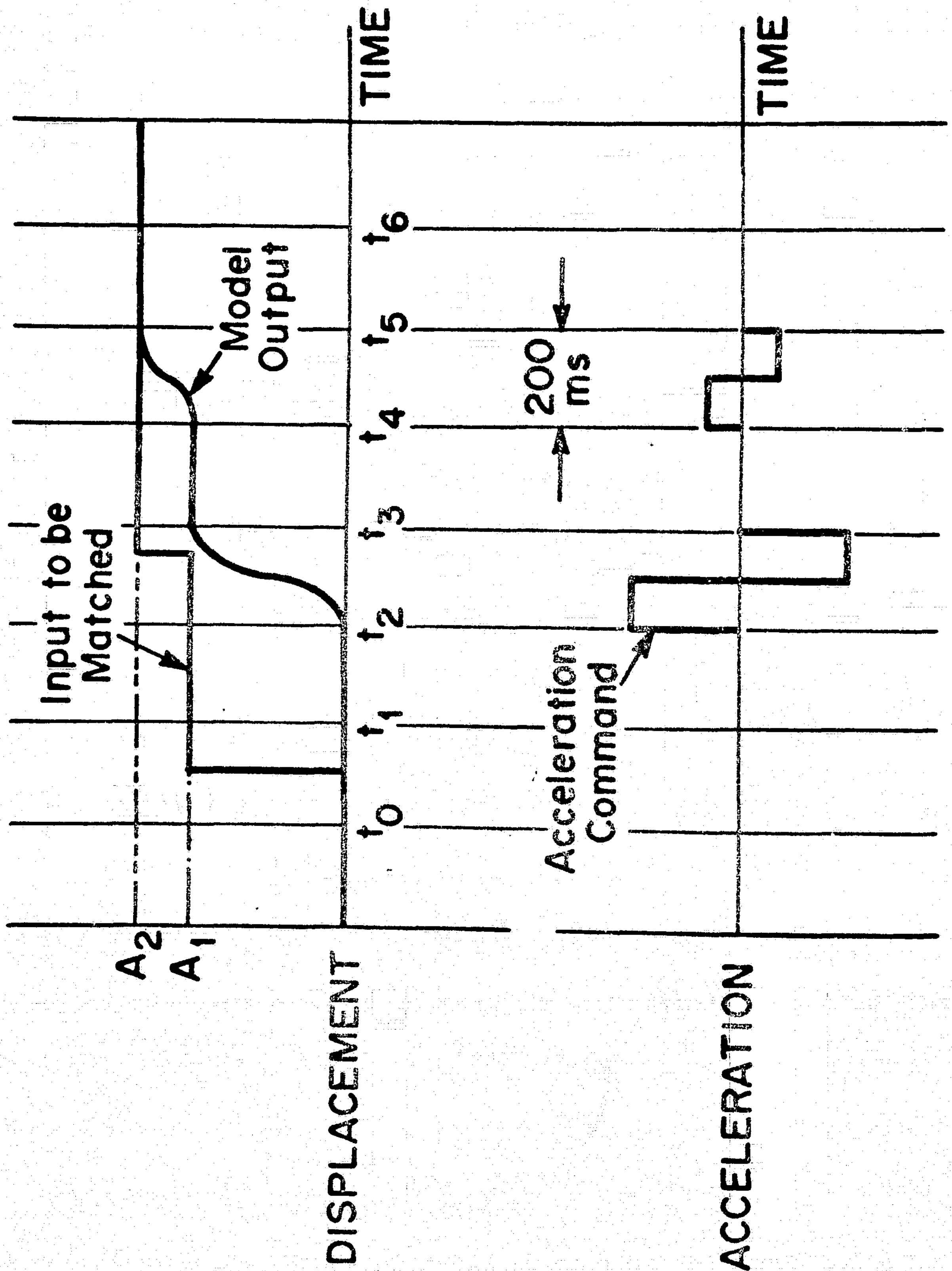

Fig. 4. Time history of the model output and the acceleration commands produced in response to the step input signal shown. This response is derived from the model of Lemay and Westcott (1962).

How does the model decide what magnitude of correction to introduce? It is to this aspect that we turn our attention next. This process begins with the Signal Comparator. In general, the Comparator is the element of the system that examines the correspondence between the desired result and the actual output produced and generates a correction signal that represents the change in output that is needed to make them correspond. The general case will become important later, but in this instance of simple compensatory control the Signal Comparator has the trivial role of comparing the displayed error signal with the desired state of zero error and transmitting a signal corresponding to the difference, which is, in fact, the error signal itself.

Consider next the Short-Term Predictor. This element is simple in concept but important to the representation of the subject's behavior. It takes the error transmitted from the Signal Comparator and computes its instantaneous velocity or rate of change. The output of the Short-Term Predictor is a signal that comprises the weighted sum of position plus velocity of the error signal. The assumption embodied in the introduction of this element is that the subject does not execute error corrections on the basis of position errors alone, but rather takes account of trends and rates of change of the error signal in making his decision about what size correction to make. Poulton (1952) defined this kind of prediction as <u>perceptual anticipation</u>, and it is one way that the subject partially compensates for the intrinsic delays he introduces into the overall feedback system. The relative importance of position and rate information is specified by a weighting constant, a parameter of the model that is selected to produce good correspondence between the model and the subject's behavior.

Because the model operates on a discrete time base, executing one response every 200 msec, the Motor Command Generator needs information about what response to produce only once every 200 msec. This fact, together with the assumption that the subject has an effective time delay in executing responses on the basis of perceived error, results in the sample-and-hold elements in the model. Once every 200 msec the sampler takes a reading of the magnitude of the desired error correction at the output of the Short-Term Predictor. That value is held in store for one sample period (200 msec) and then released for execution in the form of a movement by the Motor Command Generator. Thus movements are always being executed 200 msec after the errors to which they are responsive have been sensed.

With the exception of the Memory Loop to be considered in a moment, all the machinery is at hand to begin following signals. To make its operation clear, consider the model's response to the series of step input commands shown in Fig. 4.

The sampler takes samples at t_0, t_1, t_2, etc. At t_0 no error is detected and no command programmed. At t_1 an error of amplitude A_1 is detected. Since the rate of change of error is zero at t_1, an error correction is set up and held for one sample period and the pair of acceleration pulses is executed as shown beginning at t_2 to produce the movement shown. This movement is completed at t_3. Meanwhile the sampling element takes a new sample at t_2 and senses the same error of magnitude A_1. This creates a logical difficulty, since a correction for this error has already been implemented and is about to be triggered off. The solution to this difficulty is provided by the Memory Feedback Loop. Its function is to feed back to the error detector the magnitude of corrections already accounted for, so that they may be subtracted from the detected error and not corrected again. Thus, the effective error detected at t_2 is zero and no new error is sensed. As a result, the output remains constant between t_3 and t_4, the time when corrections sensed at t_2 would be executed. It should be clear that the concept of such a memory feedback path is necessary in any system in which there are delays in response execution. In essence it implies that the subject must take account of his "intentions" to act in planning the next correction.

Continuing with the example of Fig. 4, a new sample is taken at t_3. An error of magnitude $A_2 - A_1$ is sensed and a new correction is held and executed during the interval t_4 to t_5. The sample at t_4 detects no new error beyond that already accounted for at t_3 and no further corrections are needed.

When Lemay and Westcott (1962) compared the performance of this model with that of real subjects, it was found that the model accounted for approximately 90% of the operators' output. The model also produced time histories of tracking performance that were remarkably similar to the actual subjects' output point by point in time. Although it was not tested in this way, it seems likely that the model would also produce error scores as a function of input bandwidth not unlike those from Elkind's experiment shown in Fig. 2.

There are two main reasons for introducing this rather mechanistic description of simple tracking behavior. The most important one is to point out that at this level the process of tracking can be represented without placing much demand on human intellectual abilities. The ability to make simple positional corrections is always with us, and this basic correction system produces outputs that confound the observation of more sophisticated levels of programming organization that we as experimenters would like to examine in isolation.

The other reason for introducing it is that the performance of this kind of task embodies many of the fundamental properties of motor control. As we will see in later developments of this chapter, these component processes, such as error detection and motor command execution, become the building blocks of higher levels of skilled performance.

It would be possible to analyze some of these processes in much greater detail and to consider their relationship to what is known about the motor physiology involved (see Houk & Henneman, 1967; McRuer, Magdaleno, & Moore, 1968). However, such detail is not really germane to the picture I want to present and would divert us from the present discussion.

On the relations between discrete and continuous models of tracking performance. All of the foregoing discussion has taken the view first put forward by Craik (1947) that the performance of skills is discontinuous. Craik (1947) argued that man behaves like an intermittent correction servo system. However, the student of skills should be aware that virtually all of the predictions derived thus far from discrete representations can be predicted equally well by a continuous linear transmission system represented by a differential equation that includes a time delay but makes no assumptions of discontinuity in the human motor system (McRuer & Jex, 1967).

The difference between a discrete and continuous representation can be likened to the difference in locomotion of a caterpillar and a snake. The caterpillar moves his head and waits for his tail to catch up before initiating a new movement, while a snake moves his whole body continuously.

In either case there will be a finite time before the tail reaches the point the head just left. Thus both discrete and continuous representations imply a delay in the transmission of signals. The sampling system described in Fig. 3 produces the delay by assuming intermittent sampling and response execution, while a continuous system model implies continuous adjustments on the part of the subject with the output always delayed with respect to the input by a finite time interval.

It is beyond the scope of this chapter to present a detailed illustration of models based on continuous linear differential equations. They have much to recommend them for many practical applications (Frost, 1972; Weir & McRuer, 1970) and for some theoretical purposes (for example, see Pew & Rupp, 1971). Their success emphasizes the point that it is the processing delay rather than any intrinsic discontinuities imposed by the subjects that produces many of the qualities of human tracking performance. Just how important that role can be is illustrated by Pew, Duffendack, and Fensch (1967a). Subjects were instructed to minimize their tracking error while following a very low-frequency since wave (0.01 Hz) as accurately as they could with a compensatory error display and a rigidly-mounted force stick similar to that described earlier. The output of the control stick was artificially delayed by recording the output on a tape recorder and immediately playing it back through the playback head of the recorder. By varying the speed of the tape drive it was possible to produce transport delays of 180, 360, 720, and 1440 msec as well as the condition of no delay, in much the same way that delayed auditory feedback experiments are conducted. The subject saw the difference between the desired pattern and the delayed results of his own control actions on the display. Since the sine wave pattern was changing so slowly, the main component of the subject's response served to correct for the inaccuracies he had produced himself.

Figure 5 shows what a profound effect the tape-recorder delays had on the subject's performance as represented by the power spectrum of the error signal, that is, the average power at each frequency. These spectra have a well-defined periodic structure consisting of only odd harmonics. Consider the case of 360 msec delay. The lowest frequency peak occurs at 0.90 Hz. The subsequent peaks occur at approximately 2.70, 4.50, 6.30 Hz, etc.: the third, fifth, seventh, etc. multiple of 0.90 Hz. It is particularly interesting to note that the fundamental spectral peak shifted systematically to lower frequencies with increasing tape-recorder delay and that the case of no external delay appears to be an orderly extrapolation from the cases with delay added to the system.

These spectra are consistent with the behavior of the model of Fig. 3. Suppose that the subject perceives his error and produces a discrete correction that appears at the output after a time corresponding to the sum of his intrinsic delay together with the added tape-recorder delay. Such a strategy would produce periodicities in the output or error signal with a period of twice the total time delay or at a frequency corresponding to the reciprocal of that period. Taking these assumptions, it is possible to work backward from the observed spectra. For the case of 360-msec external delay, for example, the fundamental peak occurs at a frequency of 0.90 Hz. The period of one half cycle at this frequency is 555 msec. Subtracting the external delay of 360 msec leaves us with an estimate of the subject's internal processing delay of 195 msec. For the three subjects and five delays studied in this experiment, the range of these estimates of internal

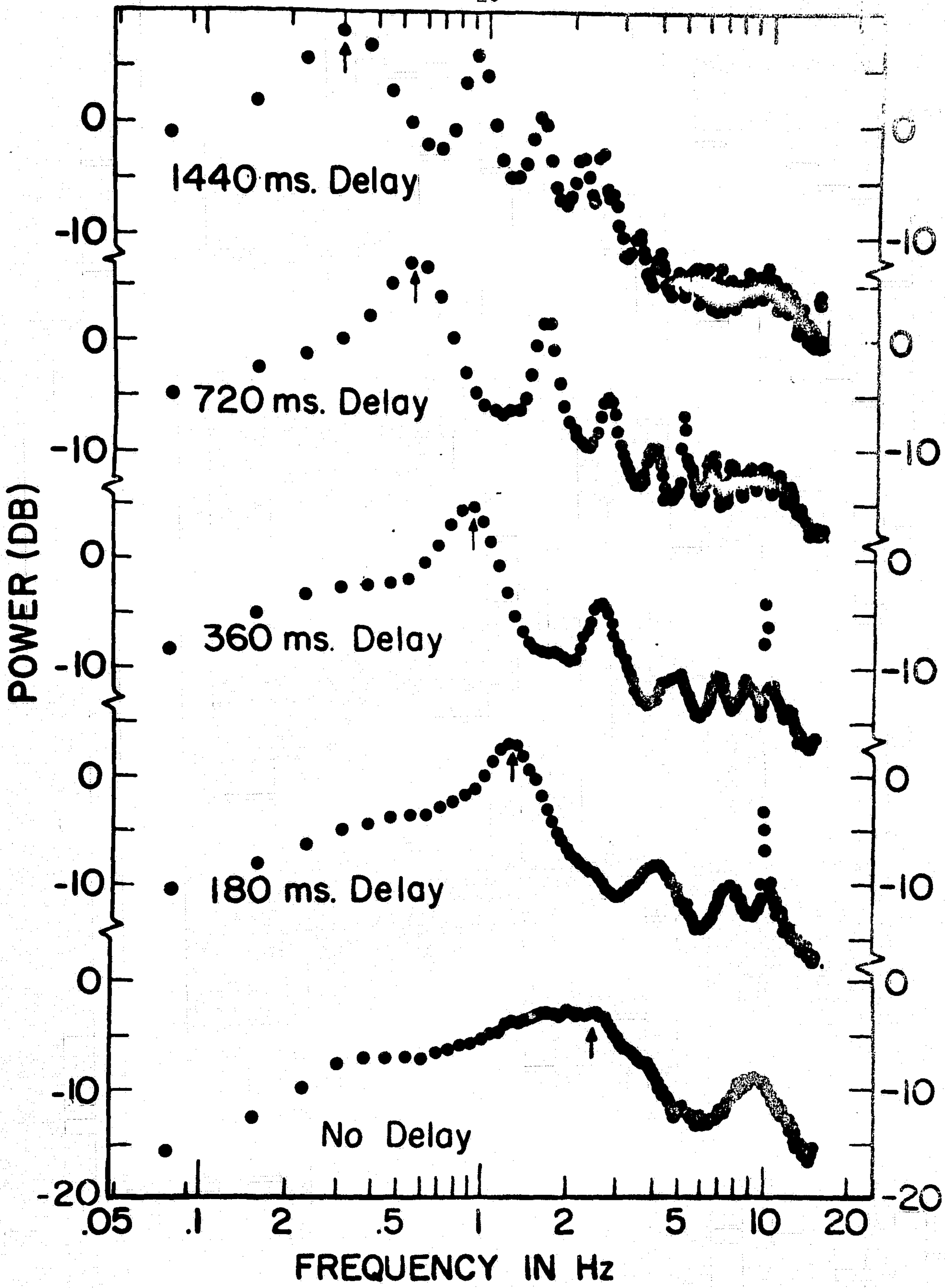

Fig. 5. The effect of introducing an external time delay into the tracking loop on the power spectral densities of the tracking error velocity. Velocities were analyzed instead of error directly in order to obtain a computer scaling advantage at high frequencies. These velocity spectra may be translated into error power spectra by subtracting 20 $\log_{10} 2\pi f$ throughout the range of f, the measurement frequency in radians/sec. (reproduced from Pew, et al, 1967a).

delay was between 179 to 212 msec, with a mean of 198 msec, a very reasonable estimate for a subject's delay in processing visual signals.

Second, and more importantly for the main thread of this discussion, it is possible to derive substantially equivalent predictions from a linear continuous model of the sort previously described. Although it is not particularly intuitive, it can be shown in general that if a broad-band noise of the sort produced by human-sensing and response-execution errors is recirculated through a system having a time delay but no discontinuous elements, the output will still exhibit the kind of periodic resonant peaks shown in Fig. 5. Further, fitting parameters to such a model in the manner I have just shown for the discontinuous model produces values for effective time delay that are just as plausible as those given above.

After working for several years to try to decide whether a discrete or a continuous representation was more appropriate, I have found no prediction that unambiguously distinguishes the two possibilities and have concluded that while the discrete representation is more intuitively compelling, both kinds of analyses are useful and provide different perspectives and insights into the nature of performance at the level of the simple corrective feedback system.

Summary. This section has described the performance of a subject in a simple tracking task in which the signal to be followed is essentially unpredictable. Under these conditions we know enough to formulate rather detailed models or specifications for what mechanisms or processes are needed to produce performance equivalent to that of our human subject, and these models involve very little "intelligence." Nevertheless, taken in a broader perspective, many properties of motor performance in general are manifestations of this simple feedback system. It is always with us and takes over a controlling position in behavior early in practice or when higher-level control mechanisms to be considered next fail to produce desired results.

Higher-Order Control Mechanisms in Tracking

If the elemental servomechanism that has been the focus of discussion thus far were our only means for dealing with changing environmental conditions, automobile speed limits would be severely restricted, many sports activities would be reduced to trivial interest, and penny arcade games of skill would never have been developed. The fact is, however, that we have a variety of mechanisms for taking advantage of the predicatability in our environment, and it is to these aspects of performance that we turn next.

Sources of signal predictability. There are several lines of evidence supporting the role that predictability can play in enhancing tracking performance. Simply providing the subject with a pursuit display, instead of the compensatory one described previously, produces reliably better tracking performance for just about all conditions that have been studied (Poulton, 1966). Since the pursuit display provides input and output information separately as well as permitting inferences about the error signal, it is generally assumed that it permits the subject to formulate commands on the basis of the pattern and predictabilities of the input signal unconfounded by the output signal.

A further improvement in tracking performance results if the concept of viewing the input independently is extended to include a preview of the path to be followed in advance of the time when control actions must be taken, such as are provided to the automobile driver when he looks down the road (Crossman, 1960; Johnson, 1972; Poulton, 1954). The amount of preview that can be effectively utilized depends in part on the complexity or bandwidth of the input signal to be followed (Johnson, 1972). Johnson showed that the major reduction of error was contributed by the first 100 msec of preview and that it produced much smaller improvements out to a preview of 1.0 sec, but only when the bandwidth of the input was extended to 1.0 Hz, that is, when there was little significant power (or amplitude) in the input signal above a frequency of 1.0 Hz. With a bandwidth of 0.5 Hz, only 100 msec of preview was useful, and when the bandwidth was reduced to 0.25 Hz, preview appeared to be unnecessary for good performance.

Poulton (1952) used the term anticipation rather than prediction and has distinguished between receptor anticipation, that based on extra information provided by modifying the presentation mode, such as preview, and perceptual anticipation, that based on the subject's ability to learn the predictabilities of the input. While I recognize this distinction, it is not particularly important for this discussion, because the mechanisms with which I want to deal are more concerned with taking advantage of the fact of predictability than with the source of this predictability; it just happens that some modes of presentation make it easier to predict than others.

Poulton, in the same paper, also describes effector anticipation, a further source of advantage for pursuit and predictive displays, in which knowledge of the effects of motor commands is available in terms of the system responses they produce. This concept will be dealt with in detail in a later section.

The ultimate in predictability is achieved when the input signal to be followed is repetitive or periodic. A triangular, square, or sine wave is a limiting case in which the periodicity becomes obvious almost immediately, but repetitive signals having complex wave forms and arbitrarily long periods become more and more predictable with practice. In principle, after sufficient practice with such signals, they should produce tracking performance that approaches that produced from tracking sinusoidal signals having comparable frequencies.

Sine-wave tracking as an example. The tracking of sine waves provides an interesting illustrative case for the advantages of dealing with predictable signals. In a study by Pew, Duffendack, and Fensch (1967b), three subjects practiced tracking pure sine waves with frequencies ranging from 0.1 to 5.0 Hz with an arm control stick for 32 daily one-hour sessions. A variety of system variables were manipulated, but the main results are shown in the three-dimensional plot of Fig. 6. In the figure each block represents four one-hour daily sessions of practice. During each four-day block, performance was evaluated at each of the five input frequencies shown for both pursuit and compensatory displays. The vertical axis displays the average performance of three subjects as measured by their mean integrated-absolute-error score.

At the lowest frequency, 0.1 Hz, practice effects were rather small, a pursuit display was only slightly better than a compensatory one, and the subjects appeared to follow the signal point by point in time by using the kind of error-detection scheme previously discussed. The

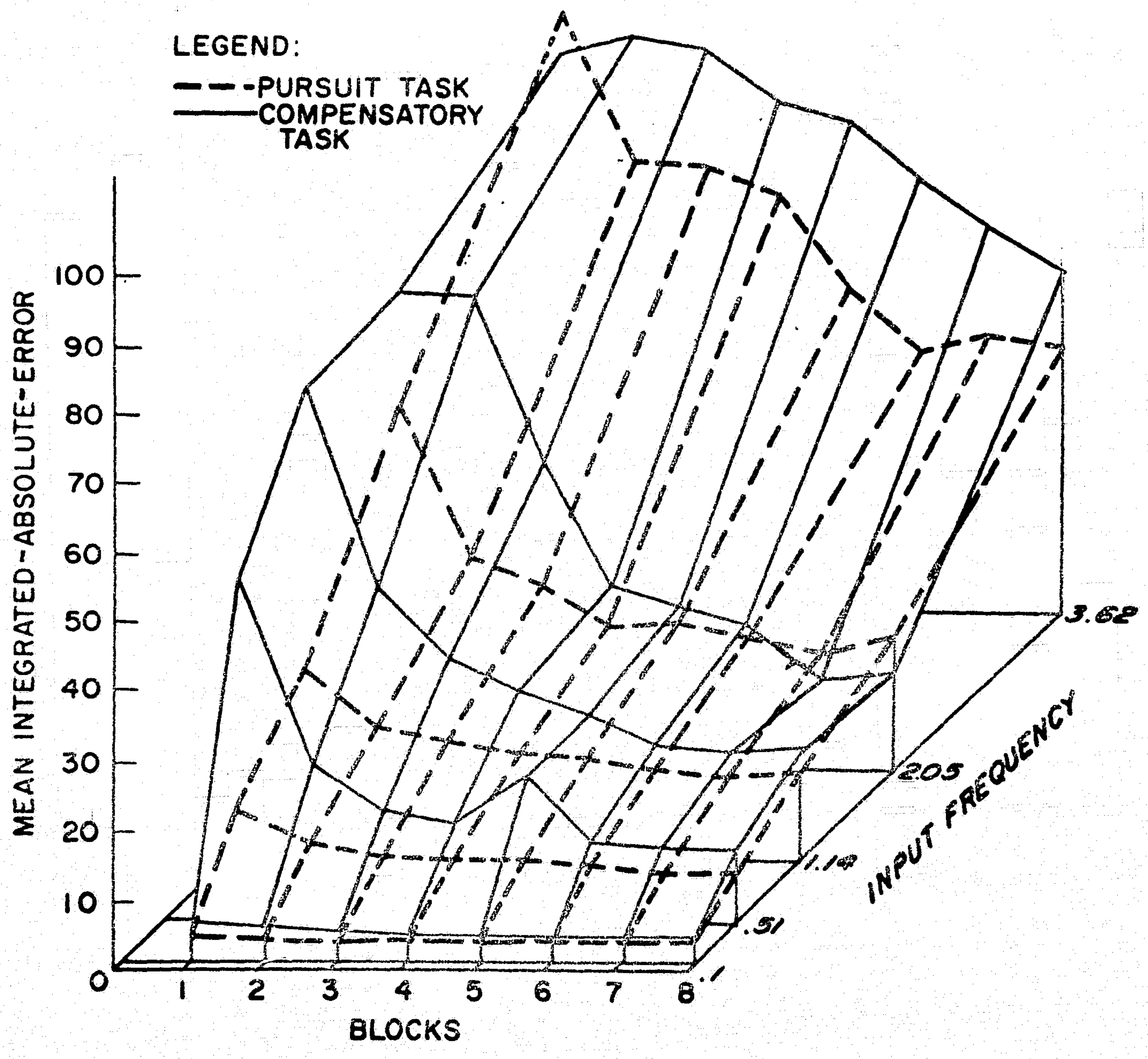

Fig. 6. Integrated-absolute-tracking-error as a joint function of blocks of practice and input frequency for pursuit and compensatory displays (reproduced from Pew, et al., 1967b, Fig. 1).

advantages of predictability were slight in this case where the period of the signal (10 sec) was long with respect to the intrinsic delays imposed by the subject. However, with the higher input frequencies, the differences in performance with the pursuit and compensatory displays were much larger for Block 1. As practice was extended, however, performance with the compensatory display still approached that of its pursuit counterpart. At 3.62 Hz, it did not make much difference what kind of display the subject had--even after 32 days of practice his performance was 2 or 3 times worse than it was at 2 Hz. The data provide an interesting precautionary note to experimenters who think tracking a sine wave of a frequency as low as 0.5 Hz is relatively easy. Even after 16 days (Block 4) compensatory display performance was still improving.

The role of signal predictability was clearly evident in this experiment. With a pursuit display and with frequencies above approximately 0.75 Hz, the subject could detect the sinusoidal pattern almost immediately. He made use of this information to generate his own approximation to a sine wave and attempted to synchronize his generated pattern with the desired input pattern. In the range of frequencies between 0.75 and about 1.5 Hz, it was relatively easy to produce this synchronization. As the input frequency was increased, it became harder and harder to produce synchronization, and more and more practice was required to do so. With a compensatory display, however, even at relatively low frequencies it took substantial practice to make use of the input pattern predictability, but as that was achieved, compensatory display performance began to look much like pursuit performance. The transition point between 0.5 and 1.0 Hz was critical. Below this frequency the subject appeared to operate on the signal moment by moment in time, making use of the regularity to obtain good predictions of the corrections that were needed. However, he was still operating in a discrete correction mode, and the frequency content of the error signal looked much like it does for very low frequency signals (see Pew, Duffendack, & Fensch, 1967b).

Above this critical frequency the mode of control changed. The subject shifted from an error correction mode to a pattern generation mode. Whereas at lower frequencies he was restricted to making corrections on the basis of short-term predictions of the error signal alone, now the error correction mechanism took on a new role, that of assessing the difference between the amplitude, frequency, and phase of the sine wave he was attempting to generate and the same parameters of the input sine wave. This kind of higher-level correction process was clearly evident in the time histories and spectra of the error signal when the task was to track frequencies of 1.0 Hz and higher.

It is interesting to note as an aside that the transition point between 0.5 and 1.0 Hz was also critical in the buildup of error in Elkind's experiment depicted in Fig. 2. In the case of Elkind's random signals, no mode switching was possible, and the error continued to build up rapidly. The pursuit display was able to sustain good performance out to somewhat higher frequencies, however, even with these random signals.

Magdaleno, Jex, and Johnson (1970) carried the analysis of modes used in tracking sine waves one step further in studies they conducted in support of their Successive Organization of Perception Model. They argued that the pattern prediction and generation mode began at approximately 0.5 Hz and that prediction and generation were used in combination with an error correction mode up to 1.0 Hz. From 1.0 to approximately 1.7 Hz, the subject used a relatively pure form of prediction and generation, and above 1.7 Hz, it became increasingly difficult to achieve good synchronization. The subject just did his best to make the two match, but the parameter matching mode became relatively ineffective above approximately 2.0 Hz. They supported these assertions with quantitative measurements of performance together with the subjects' rather interesting introspections when tracking different frequencies. The latter are reproduced in Fig. 7.

The subjects' use of pattern generation is reflected in their comments about how they took advantage of the rhythm in the frequency range from 0.5 to 1.5 Hz. Magdaleno, Jex, and Johnson (1970) also put sine wave tracking in the context of input signal predictability more generally in a way that is entirely consonant with the perspective I am presenting here. They argue that it represents the most easily predictable end of a continuum that extends to very complex waveforms that repeat after arbitrarily long periods and that become subjectively predictable like sine waves only as a function of extended practice. The frequency content of these complex but highly over-learned waveforms will dictate the mode of control that will predominate after this level of predictability has been achieved.

An example of this complex end of the continuum is provided in a study I conducted with C. D. Wickens. (See Pew, 1974). Subjects were required to track a one-minute signal, the first and last 20 sec of which changed randomly from trial to trial, but in which the middle 20 sec was repeated exactly on every trial. The amplitude distribution and frequency spectrum of the random pattern from which the middle segment was drawn

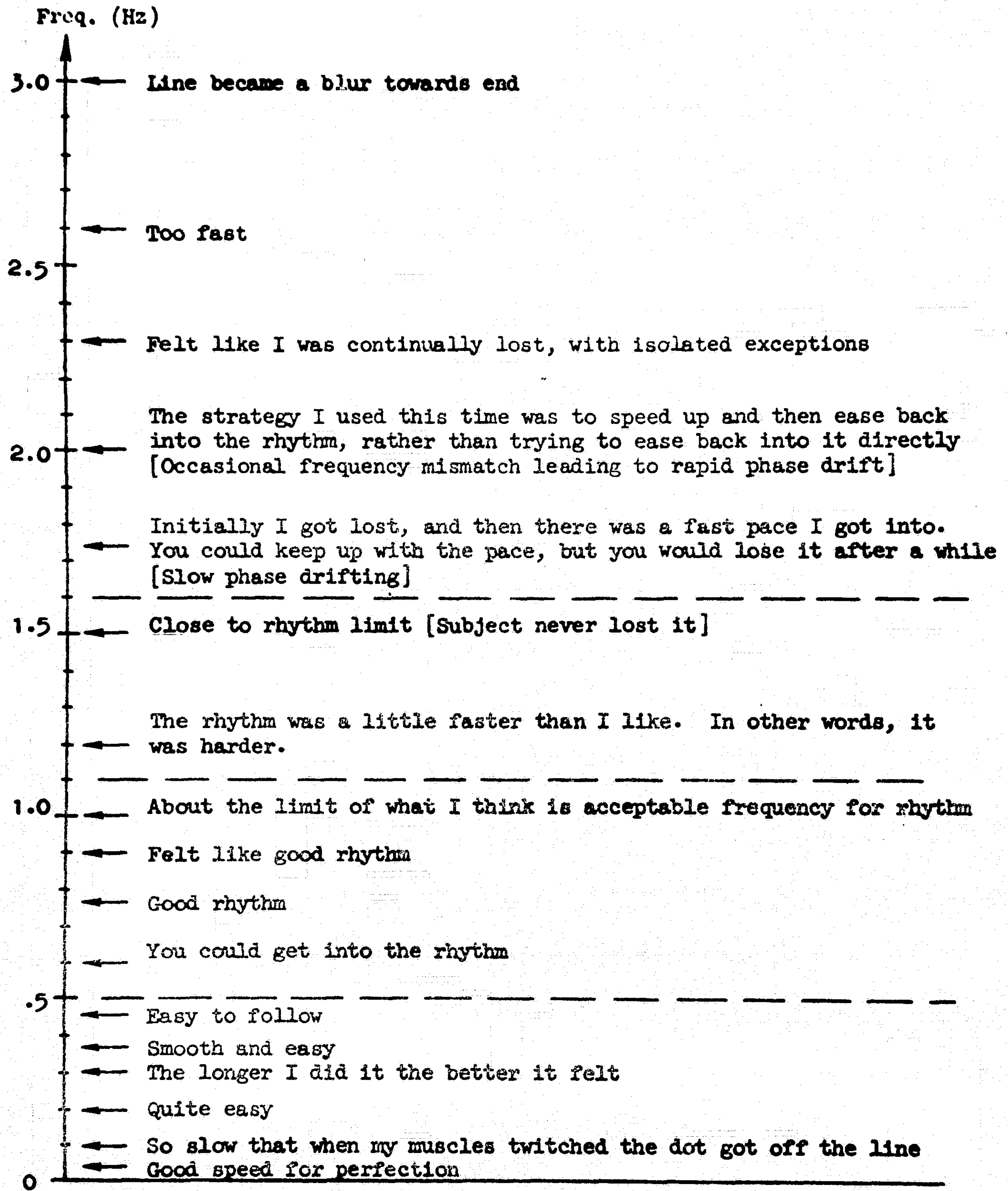

Fig. 7. Subjective comments concerning the difficulty of tracking sine waves as a function of the input frequency. Experimenter's comments are in brackets. (After Magdaleno, et., 1970, Fig. 5).

were identical to that from which the changing first and last segments were drawn. Thus on the first trial the subject had no reason to believe, and was not told, that there was anything special about the middle segment. As a function of practice, performance on all three segments improved. However, the performance advantage of the middle segment gradually increased in comparison with performance on the first and last segments that served as controls. After 11 one-hour practice sessions, integrated absolute-error on the repeated segment was 15% lower than that on its random counterparts. The subjects had obviously learned to take advantage of the extra predictability of the repeated piece, although interestingly they had only a very diffuse idea of why they were doing better. After 16 sessions they were 28% better on the repeated piece and presumably would continue to improve to the level comparable to that of a completely predictable signal, such as a sine wave, given sufficient practice.

A generalization of the control theory model. These examples provide the ingredients and the motivation to examine how the elemental correction servo system can be generalized to account for a subject's abilities to deal with signal predictability. Some of the answers have already been suggested. In the simple model presented earlier the motor system was limited to producing simple responses by introducing two equal and opposite pulses of acceleration that the muscle system then converted into smooth parabolic movements lasting exactly 200 msec. The first generalization required is to admit the formulation of motor-command strings of longer duration than 200 msec that can be more complex than the simple parabolic form hypothesized there.

A second generalization that is required to take account of the advantages of pursuit displays and preview of the path to be followed is the ability to formulate these motor-command strings on the basis of information about the behavior of the environmental input signal directly, in addition to the previously discussed ability to act on perceived discrepancies between output and input. I need to introduce an additional signal path that includes a pattern detection and generation capability but that bypasses the signal comparator and the sampling system on its way to the motor-command generator.

This generalization can be understood most easily by analogy with the eye-movement system. Our eyes are capable of two distinct modes of operation, the well-known saccadic jumps that correspond to the corrective movements described here and a pursuit movement. If a visual target is moving at a relatively constant rate the eye will follow that target with a continuous pursuit movement. The eye cannot generate such continuous movements except in response to a moving visual target and, as far as we know, is not able to generate more complex patterns of movement than simple fixed velocity tracks (Rashbass, 1961). In a model of the eye movement control, Young, Forster, and Van Houtte (1968) postulate a pursuit system that estimates the velocity of target movement directly and produces a smooth constant-velocity component of eye movement output. (See Pew, 1970, for a simplified description of their model.) If a mismatch between the target path and the eye-fixation path results, the saccadic correction system introduces a discrete correction, and the eye then either continues with the same velocity movement or takes up a new rate representing a better approximation to the target path.

By analogy, then, the way we take advantage of predictabilities manifest in the input either from a pursuit display, from preview of the course to be followed, or even from a compensatory display after sufficient practice, is by directly formulating motor commands that are responsive to our best estimates of the pattern of the input signal.

It is important to emphasize that this pattern detection and generation capability acts together with error correction to produce the behavior we observe. This is a concept that is important to the further development of the picture of motor performance I am trying to portray. A hierarchy of such mechanisms is always operating, complementing one another to produce the sometimes bewildering complexity of performance that characterizes skilled behavior.

One final generalization is required to complete the picture of how we deal with predictable signals. Whereas previously the error comparator dealt only with direct differences between input and output signal amplitude, that capability needs to be generalized to include comparison of estimates of higher-level parameters of the input and output signals. In the example of the pursuit eye movement system it was argued that velocity estimates of the input signal were made and smooth, constant speed movements of the eye were produced. Then a comparison was made between the produced output velocity and the input velocity estimates, and a revision of the generated velocity was introduced to bring these two into correspondence. A multilevel model of this sort has also been proposed by Gibbs (1970).

This capability for estimating discrepancies between input and output in terms of parameters of the input pattern is even more important in the case of repetitive signals such as a periodic step input or sine wave. The effects of predictability of various parameters of the pattern on step input tracking are nicely summarized in Noble and Trumbo (1967).

In the case of sine waves above 0.5 Hz, it is the capability to make this kind of comparison and adjustment that makes it possible to produce synchronization by subtle adjustments of the frequency of the pattern. Presumably such adjustment processes operate on the sine wave amplitude as well. Since at least one cycle of the signal is required to estimate frequency discrepancies, it seems likely that the time delay in executing adjustments to produced frequency or amplitude should depend on the frequency being generated, and this delay is over and above that due to intrinsic processing delays.

Figure 8 represents an attempt to incorporate these generalizations into the block diagram of Fig. 3. While Fig. 3 has been translated into a working simulation of the behavior of a subject performing a random signal tracking task, Fig. 8 should be regarded as nothing more than a conceptual summary of the generalizations to that model. At this point in the development of my thinking it represents a kind of logical flow chart of the operations that seem necessary, and while I believe that it can be reduced ultimately to the level of an operating computer program, I have not attempted to do so as yet. In the diagram the input signal is introduced into both the signal comparator and the pattern detector. Whereas before, with a compensatory display, only the error signal was available to the comparator, now both input and output are available separately. The role of the pattern detector is to identify the predictable aspects of the input signal that can be used to formulate motor commands over time spans longer than can be accomplished by the error

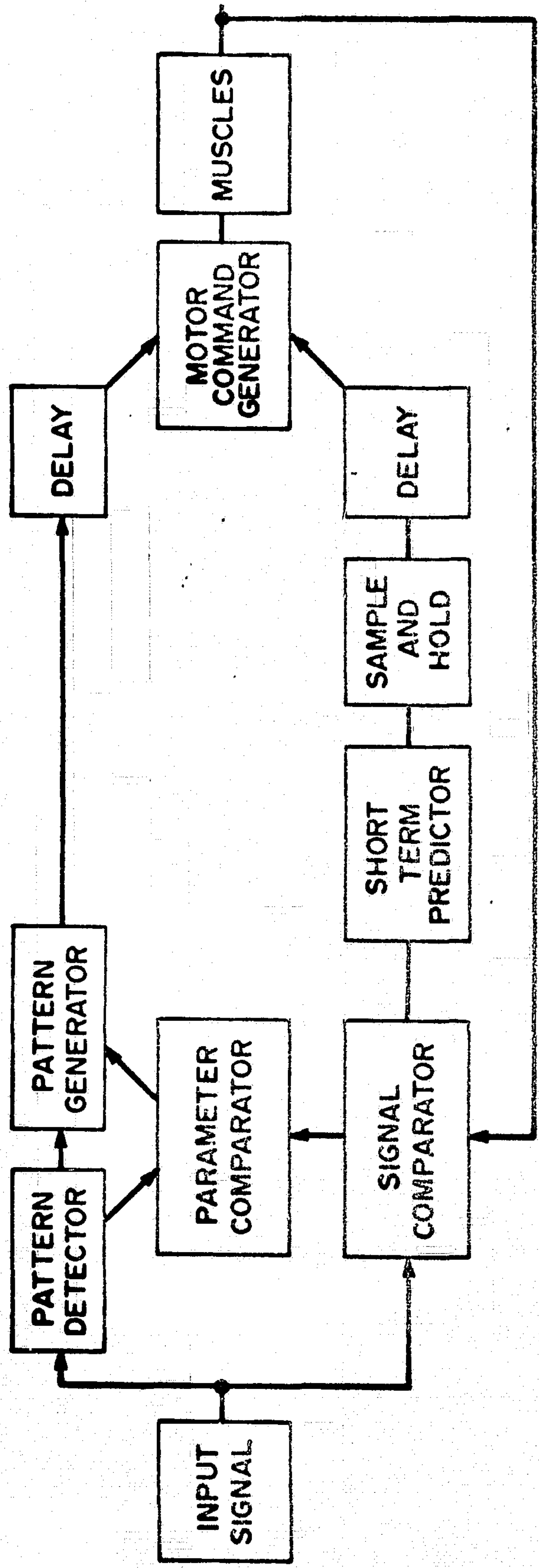

Fig. 8. Generalization of the block diagram of Fig. 3 to include the effects of signal predictability.

sampling system. At the simplest extreme this may mean nothing more than estimating segments of the input that can be usefully approximated by a constant velocity component of the output. In a more complex task it may mean estimating the parameters of the amplitude, frequency, and phase characteristics of an input sinusoid. With these parameters available a pattern corresponding to them is generated and, after a processing time delay, translated into the appropriate set of motor commands. The Parameter Comparator may be regarded as a higher-level aspect of the Signal Comparator. It is this element that transmits corrective information to the pattern generator on the basis of discrepancies between the pattern actually generated and the desired pattern. Note that this corrective information takes the form of required changes in amplitude or frequency, not the kind of discrete corrections generated by the error sampling system. The role of this parameter comparator is best understood in the context of repetitive signals for which adjustments taking substantially more than 200 msec are important for improving tracking performance.

The location of the processing time-delay element is not too important, but it is important to recognize that changes are not implemented until the processing delay has elapsed, and this is a delay in addition to any delays produced by the finite time it takes to detect changes in parameter values. Synchronization with repetitive signals is achieved through the comparators by noting that a phase difference between input and output exists due to the processing delay and introducing a parameter adjustment to compensate for this delay.

One final note concerning the time span of pattern generalization is in order. Many motor theorists have postulated the concept of a motor program, a pattern that is fired off "open-loop" without the benefit of feedback. The position taken here, especially in the context of a tracking task, is that no behavior is undertaken completely open-loop unless the stimulus conditions are so impoverished that there is no alternative. What happens instead is that patterns are generated, and they may be formulated for arbitrarily long periods into the future, but that the signal and parameter comparators are working all the time and serve to modify the generated patterns as needed. At the brief end of the scale, discrete positional commands cannot be modified oftener than once every 200 msec. Pattern commands can be expected to have a longer minimum time before they can be corrected, but given that the signal comparator is not detecting discrepancies, a periodic signal may continue to be generated without modification for arbitrarily long periods. Studies of sine wave tracking in which the input signal is turned off after synchronization has been achieved suggest that drift in the parameters occurs within 5 to 10 seconds (Magdaleno et al., 1970).

As early as 1960, Krendel and McRuer (1960) proposed a series of control modes to describe how a subject utilizes the coherence or predictability of the input signal. The most recent statement of this model is reported in Krendel and McRuer (1968). According to this theory, which they call "Successive Organization of Perception," early in practice with either a compensatory or pursuit display the subject behaves as if he had only error information in accordance with the low-level servo system described here. As the subject gains experience, especially with a pursuit display, but also with a compensatory display as a result of knowledge gained from observing the pattern of movements of his control stick, he begins to operate on the input signal directly to produce a component of the output and uses the error servo system as a "vernier adjustment" superimposed on this output. The ultimate stage of learning these authors call the "Precognitive Stage," in which pattern perception is brought into play to generate and produce an output open-loop on a preprogrammed basis for extended periods of time. Although I have not emphasized the learning aspects of tracking to the extent that they do, and my proposed mechanization deviates from theirs, I have been influenced by their development of this theory and am in agreement with many of their ideas.

Development of a model of the dynamic systems being controlled. On the output side we need to be concerned with predictability of a different kind. A fiftieth percentile male adult arm weighs approximately 3.75 kg (8.33 lbs). Some years ago Richard Vanderkolk and I tried to set up an experiment in which a subject performed a tracking task with his arm supported in an apparatus connected to a computer-driven torque-motor that reduced the effective forces required to move the arm. To the subject it felt like we had reduced the mass of his arm. Although we had some reservations about the effectiveness of our manipulation, the pilot data confirmed that upon initial exposure to this condition of reduced mass the subject produced motor commands more appropriate to the normal arm mass, and with reduced mass this led to more overshooting of movement corrections and a more oscillatory response.

This example serves to emphasize the important role played by the dynamic responsiveness of our limbs, or any physical system we are attempting to control. As a result of previous learning we begin to predict or anticipate the set of motor commands that are appropriate to produce a desired output. This ability is related to what Poulton has called effector anticipation. We might say that we build up an internal model of our own limb dynamics, or of the automobile or aircraft dynamics we are controlling, and use this model to assist in formulating the appropriate control actions. The experienced race-driver knows in great detail the effects of steering wheel and accelerator movements on his car's response, and these vary over an incredible range as a function of speed, position on the track, and a myriad of other variables. The car almost becomes an extension of his own body.

There is another analogy that will illustrate this idea. Early in the space program the National Aeronautics and Space Administration was interested in studying the effects of very high intensity noise on the fatigue strength of the materials used to construct large boosters. To examine these effects they commissioned a study to expose these materials to pure sinusoidal vibrations at 160 dB, a very loud sound indeed. The engineering problem was how to produce pure sinusoidal wave forms at this intensity. Everyone knew that if they started with a sine wave signal, any sound transmission or loudspeaker system would severely distort it, and the actual sound produced would hardly be a high-fidelity pure tone. The solution was obtained by working backwards. The engineers asked, in effect, what kind of a wave shape must we put in such that the distortions introduced by the system will leave us with a pure sine wave at the output?

The analogy is direct. In formulating motor commands the subject must utilize knowledge about the transmission properties of the muscle system, the limbs and any external devices being controlled, so that the desired output will be produced. An important component of skill acquisition is the building up of this model for the particular skill task of concern, and its fidelity or accuracy is one key to successful motor performance. All of the literature on the effects of manipulating the dynamics being controlled, differences between position, rate, and acceleration control systems, etc., can be thought of as studies of the success at building up such an internal model (see Poulton, 1966). A more detailed account of prediction based on stored representations is presented in Kelley (1968).

It is relatively easy to represent this kind of predictive capacity in the general model I am building by providing a block representing a model of the system being controlled. This block receives information from motor output and provides information to the motor program generator. It is much more difficult to say anything profound about the structure of such a model or how it is acquired.

It is clear from vehicle simulation studies with naive subjects that it is possible for a subject to acquire some knowledge of the behavior of the vehicle on the basis of vision only, that is, with a visual feedback loop reporting the results of his control actions, but with no force feel in the control and no actual motion or acceleration cues. However, it can be shown that when there is a correlation between proprioceptive feedback and visual feedback, so that the system response can be felt as well as seen, as in the case of light aircraft in which the resistance to motion of the stick reflects the actual forces on the elevator tabs, then learning to build this kind of internal model and to produce the appropriate string of motor commands is greatly speeded up and improved (Notterman & Page, 1962; Herzog, 1968).

Summary

The elemental feedback control system described in the section on inner loop control, while an important building block, is inadequate to predict performance even in highly constrained tracking tasks when either the presentation mode or the properties of the input signal to be tracked provide structure that permits us to go beyond simple error correction. A pattern detection scheme must be postulated and utilized to formulate temporally-organized motor commands that are more complex in pattern and longer in duration than simple corrections. The parameters of these more complex patterns are monitored and adjusted along with the monitoring and correction af simple positional errors, forming a series of levels at which attention and control are required--compatible with the extent of structure and predictability in the input signal. Finally, a central representation of the dynamic properties of the effectors, together with any systems in the environment that form natural extensions of the effectors, such as baseball bats, pole-vaulting poles, or bicycles, must be postulated to account for the relationships between required motor commands and effective system response, when motor patterns of any significant level of complexity are produced.

Voluntary Movement

While our knowledge of skilled performance has been advanced on many fronts through the study of tracking performance, and while there is much interest in tracking per se from the perspective of man-machine system design, the ultimate goal of much research on perceptual-motor skills concerns the understanding of the acquisition and performance of so-called voluntary movements: There are three properties that distinguish such movements: (1) the path of the movement is less important than the goal that is achieved; (2) the pattern of the movement is largely formulated internally on the basis of a backlog of experience with movements designed to achieve similar goals, and (3) the conduct of the movement is paced largely by the subject and not driven by an external forcing function.

Speed and accuracy of simple positional movements. I will begin the discussion of voluntary movements by considering the performance and theoretical analyses of simple positional movements in which both speed and accuracy are important. It is this class of voluntary movement that fits most closely the development of my analysis thus far.

The setting for this discussion starts with a subject seated before a table on which he may rest his hands. He grasps a stylus, usually in his preferred hand. On the table target circles or boundaries are indicated, and the subject is instructed to tap alternately in each of the circles, moving as rapidly and as accurately as he can between targets. In Fitts' version of this task, on different trials the targets were either of different sizes, different distances apart, or both (Fitts, 1954). The research focus has been on the time required to make movements of this sort as a function of the constraints imposed, but various investigators have examined a variety of measures of performance.

Recognition of the interrelations of movement distance, speed, and accuracy date back at least to Woodworth (1899), who also made the distinction that is still relevant today between what he called the "initial impulse" and "current control". A simple movement of the hand from one position to a well-defined target involves an initial acceleration phase, which Woodworth called the "initial impulse" and which appears to be triggered off as a unit, and a deceleration phase, the accuracy of which Woodworth showed could be influenced by peripheral feedback, hence the term "current control."

Fitts (1954) was the first investigator to formulate a quantitative expression of the relationship among distance, accuracy, and movement time, in the form,

$$MT = a + b \log_2 \frac{2A}{W} .$$

This equation, which has come to be called Fitts' Law, implies that movement time (MT) is a linear function of an index of difficulty of the movement, defined by the logarithm of the ratio of movement amplitude (A) to target width (W), the latter representing a constraint on movement accuracy. Fitts derived this relationship from informational concepts, and argued that there was a fixed informational capacity for producing accurate movements and that the trade-offs among movement amplitude, accuracy, and time embodied in Fitts' Law were a reflection of this limited "channel capacity." Although the fits to data of this equation are remarkably good, usually accounting for more than 90% of the variance in movement times, Welford (1968) has shown that some improvements in the empirical fit to the data sometimes can be made if one assumes a two-component representation, one component involving the contribution to accuracy of the initial adjustment phase and a second related to the accuracy of the current control phase, to use Woodworth's terms.

It has since been repeatedly shown that Fitts' Law can be derived from a variety of perspectives that make various assumptions about the role of feedback in control of skilled movement. Crossman and Goodeve (1963) showed that a first-order differential equation simply postulating that the velocity of movement was inversely proportional to the remaining distance away from the target led to the equation of Fitts' Law. Langolf (1973) showed that a second-order underdamped differential equation relating the acceleration and velocity of the movement to the distance away from the target also captures the temporal predictions of Fitts' Law and in addition reproduces some of the oscillatory properties of hand motion usually observed in movements of this type. The most intuitively appealing formulation was developed by Crossman and Goodeve (1963) and by Keele (1968), based on a first-order difference equation.

It is not necessary to go into the full derivation here. The importance of the model lies in the implications of its assumptions for understanding the mechanism of simple movements. Keele's derivation postulates that the subject makes an initial adjustment and as many discrete corrections to the initial impulse as are necessary to converge on the target area. He explicitly assumes that each correction takes exactly the same amount of time to complete and uses estimates of the time necessary to process visual feedback for the value of the time between successive corrections. An experiment of Keele and Posner (1968) estimated this time to be between 190-260 msec. The derivation of the model also assumes that the average accuracy of a correction is a constant proportion of the distance moved, and Keele takes the constant of proportionality to be between 0.04 (Woodworth, 1899) and 0.07 (Vince, 1948, Exp. IV).

With the time equal to 260 msec and the accuracy constant equal to 0.07 Keele reports that he can fit the slope of the Fitts' Law function reported by Fitts and Peterson (1964) quite nicely. Although this model has great intuitive appeal, I never took it to be more than an analogy to real performance until Langolf (1973) performed a Fitts' Law experiment in which subjects manipulated a probe-mounted peg under a 10-power microscope, simulating the performance of microscopic assembly operations. He obtained time histories of the motion profile of the probe used to move the 1.1 mm. diameter peg distances of 1.27 or 0.254 cm into holes of varying tolerances. He found the Fitts' Law prediction quite satisfactory for this performance under a microscope. Moreover, by performing ensemble averaging of the motion trajectories of several of these movements he found clear evidence for discontinuities in the path to the target and, amazingly, the times (200 msec per correction) and movement accuracies were not inconsistent with Keele's estimates.

Beggs and his colleagues, in a series of reports beginning with Beggs and Howarth (1970) and including Howarth, Beggs, and Bowden (1971), have formulated a different analysis of a similar aiming task that is particularly interesting because it utilizes some assumptions very similar to those of Keele. The task on which their analysis is based involves repetitive aiming at a vertical line target. Whereas virtually all the empirical studies of Fitts' Law have used a target of defined width and instructions to move as rapidly as possible consistent with achieving the required level of accuracy (see Fitts & Radford, 1966, for one exception), Beggs and Howarth chose to instruct their subjects to be as accurate as possible and to constrain movement speed by pacing them with a metronome.

By measuring the duration and accuracy of various phases of the movement as a function of different movement speeds, and by manipulating the distance from the target at which they turn off target illumination, thus removing the opportunity for utilization of visual feedback, these authors arrived at some rather profound conclusions about the important variables relating the speed and accuracy of simple movements. Taking the same position as Keele (1968) and others, that a visually mediated intermittent correction mechanism is operating, they conclude that the primary determinant of movement accuracy is the distance remaining at the time the last correction is initiated. They conclude in Beggs and Howarth (1970) that the last correction is always initiated at a fixed time before the movement is terminated and take that time to be 290 msec, on the basis of analysis of aiming accuracy when the target is obscured at various times before the movement is completed. Thus they argue that the trade-off between speed and accuracy of movement is simply a result of the fact that when movements are made more rapidly, the critical 290 msec cut-off occurs at a greater distance away from the target and hence results in reduced accuracy. Their formulation of a prediction comparable to Fitts' Law results in a power function relation between speed and accuracy having the form

$$E^2 = E_0^{\,2} + K^2 \sigma_\Theta \left(\frac{t_u}{T}\right)^{2.8}$$

where E^2 is the mean square deviation of target hits from the target; $E_0^{\,2}$ is a residual noise component in motor output that might be attributed to tremor; K is a constant depending on the deceleration profile of the movement; σ_Θ is the angular aiming accuracy of movements in the absence of visual feedback; t_u is the time remaining after the last correction (taken to be 290 msec); and T is the total duration of the movement. (See Howarth, et al., Bowdin, 1971, for a detailed derivation of the formula.) They argue that their data are better fitted by this model than by Fitts' Law but point out the procedural differences between the two experimental paradigms.

Relation of simple movement mechanism to tracking mechanisms. These results and models are of interest in and of themselves for the student of skilled performance, but they also contribute some fundamentals to my growing picture of perceptual-motor skill. I find the similarities of Keele's and of Beggs and Howarth's conceptions more notable than their differences. Both postulate that visually guided movements are in fact modified during their execution, given that they are made slowly enough that at least one round of visual feedback processing is possible. When not otherwise instructed and when an accuracy constraint requires them, subjects will choose to move at a speed that will make such corrections possible. Both positions assume that the accuracy of blind positioning will be inversely proportional to the distance moved. The conception that emerges is one that fits closely with the analyses of tracking performance discussed earlier. Whereas in the case of tracking predictable signals, commands that would correspond to the initial impulse described here are initiated on the basis of predictive information obtained from the input signal itself, in this case the formulation of the initial impulse is based on information about the initial position of the hand, the perceived goal of the movement, and any other constraints imposed on the movement by the experimenter. Corrections are executed, in my opinion, not on the basis of deviations from a predetermined path, but rather on the basis of revised estimates of where the target is with respect to where the subject's hand now is. Of course, one visual reaction time must be added in to determine where the hand will be when the correction is actually initiated.

Latency of current control based on proprioceptive cues. Suppose the basis for corrections is proprioceptive rather than visual. For some time it has been maintained that proprioceptive reaction time may be somewhat shorter than latency to a visual stimulus. Chernikoff and Taylor (1952) produced some of the shortest estimates by measuring the onset of deceleration of the hand after it was allowed to begin free-falling at an unexpected time. Their estimates were between 112-129 msec. Recently Jordan (1972) conducted an experiment that confirmed the shorter latency of proprioceptive cues in a more practical context. He set a group of naive fencers on-guard against a mechanically-mounted fencing foil and instructed them to respond as rapidly as possible to a movement of the mechanical blade under three conditions. In Condition I their own fencing blade was set 15 cm away from the mechanical blade, and the stimulus for a movement was a visual observation of the moving blade. In Condition II the subject's blade was resting against the mechanical foil, and the stimulus was both visual and the proprioceptive feel of the mechanical blade's movement. Condition III was the same as Condition II, except the subject was blindfolded and had only the feel of the blade to react to. The mean response time was measured from onset of blade movement to the first change in the action potential in the flexor muscles of the fingers. After some practice, for the three conditions the mean response times were respectively 129, 136, and 109 msec. The blindfolded condition was reliably faster than either of the other two, suggesting not only that proprioception produced faster times but also that vision was dominant over proprioception when both were available (Condition II).

These results are made even more plausible by some recent work of Evarts (1973). He used a monkey as the experimental subject and a simple plunger movement by its hand as the response. When the stimulus for a corrective response was a sudden change in force on the plunger, he found EMG activity in the arm attributable to cortical involvement, with a latency as short as 30 to 40 msec. Evarts emphasizes that these were not simple spinal-level reflexes. They did not occur prior to some experience with the stimulus situation, and they did not occur when the direction of the force cue was unexpectedly changed. We must conclude that when the stimulus situation provides proprioceptive cues, the time constants associated with corrective activity will be shorter, but we have at this point no reason to propose any different mechanisms for movement execution.

Properties of Motor Memory. When we shift from tracking performance to voluntary movement perhaps the biggest gap lies in the different roles played by memory in the two cases. In the first two sections of this chapter I had little occasion to refer to memory per se, except as it is implied in prediction and extrapolation from what is given. However, when we speak of movements produced to the subject's specifications, memory becomes paramount. One is led to ask almost immediately, "What is it that is stored when we acquire the ability to perform an organized pattern of movement?"

One approach to this question has been to examine the short-term retention of the accuracy of simple movements over a specified distance or to a specified location. In the typical experiment the blindfolded subject's hand is first passively or actively moved to a stop. Then a period of rest or activity intervenes. Then the subject is asked to reproduce the movement to the same place with the stop removed. This task is frequently considered to be a movement analog of the verbal short-term memory experiment referred to as the Brown-Peterson Paradigm. It can be shown that repetition of the to-be-recalled movement improves accuracy, and it becomes necessary to distinguish the case with location cues available from the case in which only distance cues can be utilized. In general, location cues seem to be a more robust source of information on which to base storage. The greatest interest has focused on the question of whether it is possible to demonstrate interference effects by occupying the subject with various tasks during the retention interval and thereby to infer the kind of coding implied in memory. It seems clear that performance of other movements similar to the criterion movement interferes, but with the many other kinds of perceptual, verbal, or intellectual tasks that have been tried, no clear conclusion has been reached. The question of appropriate memory coding for simple positional responses remains an open and viable one. While it is interesting, I will not elaborate on this work further because it does not represent a central issue from the perspective of this chapter. The reader is referred to a review of the motor memory literature by Stelmach (1973) for a detailed discussion.

The properties of motor memory that seem particularly important to the understanding of the production of organized movement patterns are captured in the following simple exercise: Sign your name on the dotted line on your examination paper and then go to the blackboard and sign it again. The limb is used differently. Different muscles are involved. The size is different. Nevertheless, the movement pattern produced can still be clearly identified as your signature; it is unique to you. This homely example supports the interpretation that whatever it is that is stored, it is not simply a specific set of motor commands. In fact, no two repetitions of the same movement are ever exactly alike. Bernstein (1967) distinguishes between the topological properties (spatial patterns) of a movement and its metric properties (size and dimensions) and emphasizes the dominance of its topological properties. As he says, (Bernstein 1967), referring to a similar demonstration involving drawing circles,

> "It is clear that each of the variations of a movement demands a quite different muscular formula and even more than this involves a completely different set of muscles in the action. The almost equal facility and accuracy with which all these variations can be performed is evidence for the fact that they are ultimately determined by one and the same higher directional engram in relation to which dimensions and position play a secondary role" [p. 49].

The concept of schema learning introduced by Bartlett (1958) and defined experimentally by Posner and Keele (1968) seems an appropriate way to think about the generalized nature of what is stored for the production of movement patterns. Posner and Keele trained subjects to classify distortions of nonsense dot patterns without ever showing them the prototypes from which the patterns were distorted. The subjects were then tested for recognition of the distortions they had learned, of new distortions of the same set of prototypes, and of the prototypes themselves. Recognition performance was as good on the prototype they had never seen before as on the distortions of them that they had learned. Recognition for both these sets of patterns was significantly better than that for the new distorted patterns. This experiment together with a follow-up (Posner & Keele, 1970) argues effectively that during the process of classification learning a generalized schema related to the prototype itself was built up. Although this kind of study has not been performed for motor patterns, I believe it captures the essence of the kind of schema that must be stored for the production of motor patterns.

Of course, identification of a motor schema as a critical aspect of acquiring motor skill raises more questions than it answers. What properties of a movement sequence are encoded? What properties are intrinsic to a particular schema, and what properties are only dimensional parameters that are free to vary from one execution to another?

A possible direction to pursue to answer these questions is given by a transfer condition in the study by Pew and Wickens (Pew 1974) referred to earlier. After subjects had practiced the tracking task for 11 days, in which the middle 20 sec of each one-minute trial was repeated exactly on every trial, a block of 10 trials was run in which the repeated segment was exactly reversed--wherever it moved to the left before, the signal now moved to the right, and vice versa. Under this condition the subjects' performance was significantly better on the inverted segment ($p < .05$) than their performance on the beginning and ending segments averaged together, but significantly worse than on the preceding trials with the middle segment repeated. Thus there was some but not perfect positive transfer to the inverted segment, a result that would not be expected if they had been learning a very specific sequence of motor commands. This kind of transfer paradigm, in which simple metric transformations of highly practiced voluntary movement patterns are tested, should provide fruitful grounds for gaining further understanding of the nature of motor schema learning.

The schema instance and its perceptual consequences. It is proposed, then, that a particular movement pattern, an instance, is selected from the generalized schema for movements of that particular class, such as signing one's name or drawing a circle, and it is the specific instance that actually gets translated into real movements. However, following the view put forth by Adams (1971), one further implication of the instance must be postulated. It is not enough that the instance is executed as a string of motor commands. A further consequence of the selection of an instance is that an image of the sensory consequences of actually producing that movement is also generated. Adams refers to this image as the "Perceptual Trace" and devotes substantial discussion to the way it is built up as a function of practice and to its importance as the basis for comparing expected sensory consequences with actual sensory consequences. Laszlo and Bairstow (1971) capture the same idea in their notion of a standard for comparison with actual feedback. It is the perceptual trace that makes possible the detection and, occasionally, the correction of errors in movement sequences prior to or in the absence of confirming knowledge of results about the success or failure of the pattern to achieve its goal.

Effects of feedback manipulation. Some implications of feedback were indicated in the description of models of tracking control and of models for the production of rapid, accurate simple movements, but these models represent a rather indirect approach to evaluation of the role of feedback in the conduct of a skill. More direct experimental approaches have been taken. Studies of delayed, distorted, and transformed feedback and attempts to eliminate all feedback are examples of these more direct approaches.

Experimental studies of the effect of delayed, distorted, and transformed feedback, many of which are summarized in Smith (1962), report the not surprising finding that the more degraded feedback is, the more degraded is the performance that results. For example, delayed speech (Yates, 1963), delayed handwriting (Van Bergeijk & David, 1959), and delayed tracking (Pew, et al., 1967a) all produce a tendency toward repeated elements or stuttering and a stretching out or increased number of pauses in the motor sequence. These studies suffer from a difficulty of interpretation, however. While the authors are usually interested in the assessment of the effect of modifying one or another source of feedback, manipulation of that one not only degrades it, but also places it in conflict with the remaining undegraded sources. For example, studies of delayed auditory feedback from speech have not effectively eliminated the normal feedback from the speech musculature.

There are now a number of studies, many of which are reviewed in Taub and Berman (1968), that support the contention that in higher animals rudimentary movements can be performed in what appears to be the total absence of feedback from the periphery. The most recent and conclusive report is that of Taub, Perrella, and Barro (1973), who have shown that monkeys deafferented at birth and having their eyelids sewn closed are still able to locomote and can be trained in relatively precise hand to mouth coordination. Thus, acquisition of new responses was possible as well as sustained performance in the absence of peripheral feedback. There are at least two kinds of evidence that support the generalization of these results to man. First, there is Lashley's (1917) classic analysis of a patient with an unusual gunshot wound in the spine, which produced effective sensory anesthesia of the leg below the knee. He showed that the patient could produce movements of the limb with no peripheral feedback and could even make gross judgments of the relative sizes of the different movements that he produced.

Laszlo has used a blood-pressure cuff to eliminate sensory feedback by applying a compression block on the arm. She argues that the loss of blood circulation below the cuff for 20 minutes or so produces selective loss of the afferent feedback from the hand and reports that, at least for some subjects, tapping without visual feedback was possible "under the cuff" (Laszlo & Manning, 1970). These authors also argued that some improvement in tapping rate resulted from practice "under the cuff." Having served as a subject for this procedure, I must say the subjective effects are compelling, but I feel that Laszlo's evidence should be taken as supportive rather than definitive in light of the uncertainties of interpretation of exactly what musculature and receptors are affected and to what degree.

<u>Feedback levels for goal-oriented movements</u>. Feedback concerning the results of voluntary movements operate at many different levels of specificity. Verbal reports of the results of an activity are the most global and occupy the most peripheral position in the sense that their correspondence to neuromotor events is the least direct. Next most specific in the series and somewhat closer to neuromotor events are the exteroceptors, primarily vision and audition, followed by the proprioceptors, including labyrinthine sensation, as well as the information feedback from the muscles, joints, tendons, etc.

At the level above the proprioceptors I propose to consider some central representation of motor outflow--efferent signals that provide: an "Efferent Copy" (von Holst, 1954); the "Feeling of Innervation" (Lashley, 1917); a "Copy of the Command" (Anokhin, 1969); or James' "The Idea of an Action" (see Greenwald, 1970). Greenwald, following James, actually proposes that efferent signals representing the consequences of motor activity play an active role in movement production, going beyond their role as feedback.

Even taken simply as feedback, such a concept seems necessary to explain Lashley's finding of reportably different perceptions of active movement of the patient's deafferented lower leg, and Taub and Berman (1968) argue that something resembling efferent copy is needed to explain the deafferented monkey's acquisition of a new response. If he had no image of the movement he had just made, what is it he would compare with the expected consequence and modify on the next attempt?

Actually, these are largely default arguments: They postulate an explanation for results that are otherwise unexplainable, but there is also substantial direct empirical evidence in support of such a concept. At the physiological level Taub and Berman cite electrophysiological data of Chang (1955), Li (1958), and others for efferent collateral discharge flowing back to the cerebral cortex. At the behavioral level the converging operations that support the case for an efferent copy-like mechanism are summarized by Gyr (1972) in the context of his active theory of perception.

Returning now to the levels of feedback from which this digression began, it seems appropriate to consider efferent signals as the highest level of feedback that may be kept distinct in some way from the representation of a goal-oriented schema or plan of a movement. In the absence of all lower-level feedback it is sufficient for crude monitoring of the results of a motor act, but this is rather academic since movements are seldom produced under such deprived circumstances. The real importance of this efferent copy lies in its role in the communication of what string of motor commands was actually executed, even if further downstream, at a more peripheral level, the muscular results went awry. The experiment described in an earlier section in which the perceived inertia of the arm was manipulated could be thought of as a disturbance of the relationship between proprioceptive and efferent copy cues.

A block-diagram summary of "voluntary" motor control. With the introduction of the idea of multilevel feedback my discussion of the machinery out of which voluntary movements might be built is relatively complete. The processes involved might be summarized in the form of the very tentative block diagram of Fig. 9.[3] It captures ideas similar to Bernstein's (1967) scheme of "circular control," of Anokhin's (1969) "afferent synthesis," and of Adams' (1971) closed-loop model.

The model postulates a Schema Memory as the generalized source of stored information about the organization of movements with respect to particular goals. When the stimulating conditions are such that a movement is motivated, then a specific instance is selected from the schema memory for execution. The particular instance selected depends intimately on the dynamic state of the subject and the environment at the time the selection is made. The magnitude or length of the instance depends on the predictability of the environment, and on the task demands of the movement.

A golf swing might be fully represented as an instance, whereas only the initial segments of a pole vaulter's trajectory might be formulated as an instance. The instance may be thought of as a stored representation of a path in space through which the members of the body will move. The schema instance exists in complete form at a single point in time. It is like a computer program waiting to be read.

The next stage in this hypothesized system is a translation of the stored program into a temporal string of motor commands. One can postulate that the timing scale factor of a planned movement is added at this point--the sequence can be speeded up or slowed down as a unit--and while we have some evidence that such scaling is possible (Armstrong, 1970), I certainly have no strong defense for placing the timing control at exactly this point in the sequence. Once a string of muscle commands have been formulated, all that remains is the activation of the muscles to produce a pattern of movement in space and time.

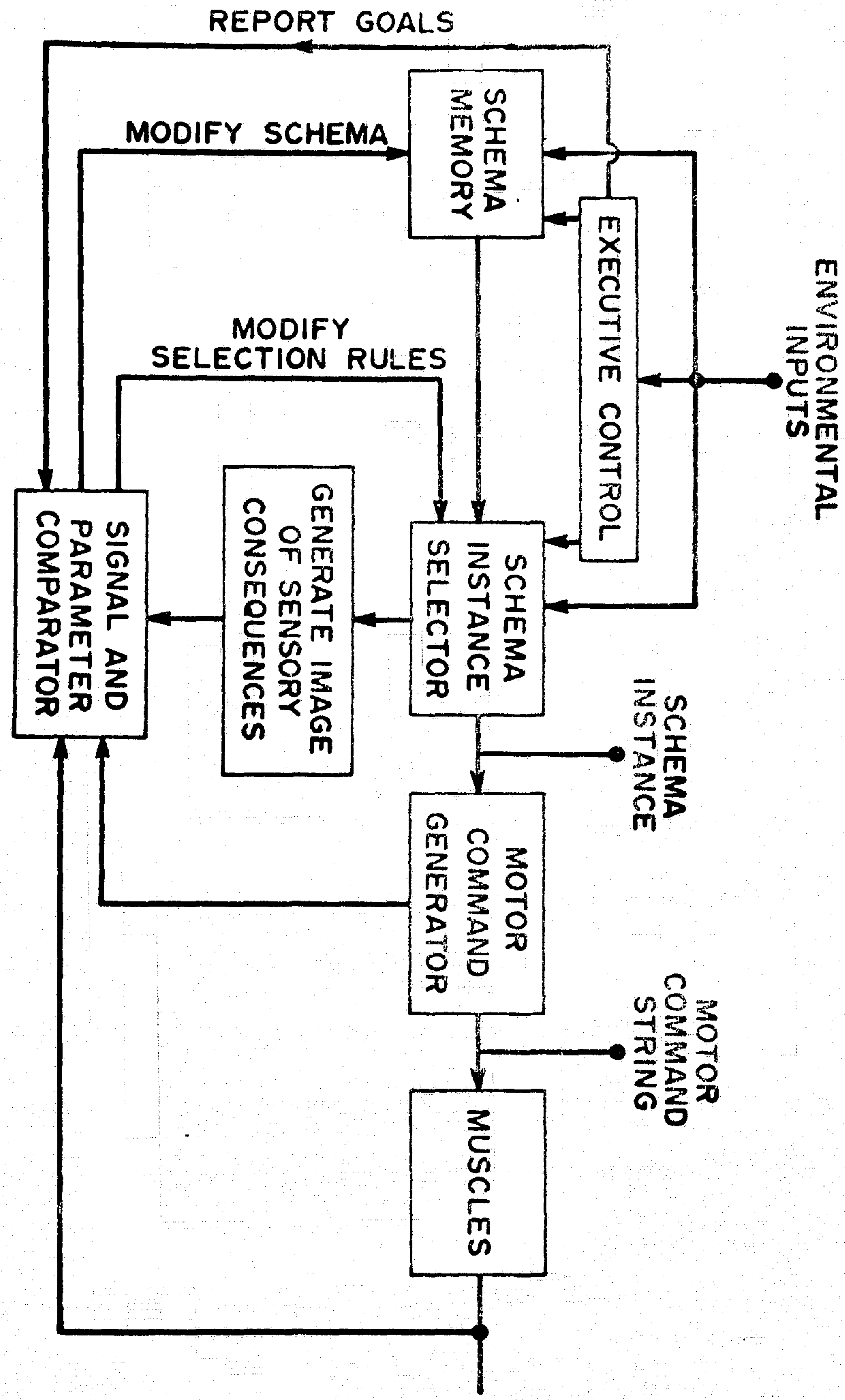

Fig. 9. Block diagram representing the essential components of a descriptive model of the performance of self-initiated movements.

As Bernstein (1967), Anokhin (1969), and Adams (1971) emphasize, an essential component of the process is the Signal Comparator. It is here that Anokhin's afferent synthesis is focused. Whereas in the case of tracking, the source of signals to be compared was straightforward, now many highly interrelated signals come into play, and it is difficult to represent them all in a block diagram and even harder to differentiate them experimentally. First, there is information about the goal to be achieved, which comes from some higher-level executive program and can be considered one level of expected consequences. Depending on the nature of that goal, feedback from vision, audition, and proprioception may be relevant to evaluating whether the goal has been achieved. Then there is the perceptual trace, an image of the expected sensory consequences. It is important to remember that the actual sensory consequences are represented at various levels of specificity, ranging from efferent copy to knowledge of results, and it must be postulated that the image of expected sensory consequences has a corresponding dimensionality, although Fig. 9 does not make this point explicit. It is equally difficult to delineate the results of this comparison operation. They fall into two main categories. First, given sufficient time, there are evaluative results that serve to modify the ongoing course of the movement pattern. Either lower-level corrective mechanisms may be brought into play, or modified schema instances might be initiated. Perhaps more important is the impact of the evaluation of the results of a movement on the course of generation of similar movements in the future.

At this time it appears to be impossible to delineate in any detail the nature of the changes brought about by experience, but they must include modifications to the generalized schema stored in memory (Adams' memory trace), modification to the interplay among environmental stimuli and the schema selection process, modification and increased specificity of the perceptual trace, and modification of the motor command sequence so that the expected consequences and the actual consequences are brought into closer correspondence.

A practical example. It is illuminating to watch a mail clerk sorting packages for outgoing delivery. The clerk stands near a source of packages some 5-10 feet away from an array of perhaps 25 mailbags attached to a rectangular frame. The sorter examines each package, decides on its destination, and then make a hefty toss to place it in the right mailbag. The novice has little initial success but the experienced sorter can hit the right bag virtually every time.

These clerks, I would argue, have built up a generalized schema for package tossing; however, they do not always stand in exactly the same place and no two packages are alike in weight, size, or shape. Thus the clerk selects an instance from the general schema in accordance with his location in relation to the bags, together with the initial conditions defined by the properties of the package. Note that both visual and proprioceptive properties are important in this case. He then initiates a temporal stream of commands that his muscles translate into a trajectory of his arm and the appropriate release point of the package. For some odd-shaped packages the orientation at the time of release is as important as the release velocity.

While it is certainly important, it is not sufficient to say that success or failure at hitting the right bag provides the knowledge of results required for improving the clerk's skill. According to the model proposed here information about the expected sensory consequences, and about the actual sensory consequences together with the success or failure of the movement pattern, all converge in the Comparator Mechanism to produce the basis for modifications to the generalized schema, the instance selection rules, and the temporal implementation of the command sequence. In some cases the clerk, especially a highly practiced one, may be able to report a failure as the package leaves his hand. It seems likely that this kind of error detection depends on a lack of correspondence between the expected sensory consequences and the actual sensory consequences, even before the package trajectory is complete. It is based on acquiring a strong a priori association between successful patterns and their expected sensory consequences.

The viability of this distinction is supported by a study by Schmidt and White (1972) that was undertaken to test predictions of Adams' (1971) theory. Subjects were required to move a slider 24.1 cm in exactly 150 msec. The movements were initiated by the subject and follow-through beyond the 24.1 point was permitted. In addition to measuring the average absolute timing accuracy, the experimenter obtained the subject's <u>estimates</u> of movement duration as a measure of the accuracy of his perceptual trace.

Performance during the training phases measured by average absolute accuracy improved as a function of practice, but more importantly the correlation between a subject's estimate of his duration and the actual duration increased substantially, indicating the build-up of association between the successful movements and their expected sensory consequences. The fact that performance was maintained at about the same level even when knowledge of results was withdrawn, and that the level of correlation between estimated and actual error increased in this case, supports the idea that the relationship between expected and actual sensory consequences provides the error comparator with a useful source of information for purpose of monitoring and adjusting the schema instance on subsequent trials. Schmidt and Wrisberg (1973), using a 55-cm, 200 msec slider movement, obtained similar results but failed to confirm the finding of sustained levels of timing accuracy under knowledge-of-results withdrawal. However, this failure could be attributed to providing insufficient practice prior to withdrawal on this more difficult task.

General Issues and Summary

The outline of this process-oriented view of skilled performance is now as complete as I can make it. If not wrong, the picture is surely incomplete. Especially with respect to voluntary movements, about all I have been able to do is organize our ignorance on the basis of logic, speculation, and some limited evidence. There are, however, general issues that I want to address from the perspectives presented here.

The question of what is a motor program and what do we mean by "automating" a movement are to me inseparable from a more global analysis of temporal and spatial organization. There is no level in the motor system at which I am willing to say, "Here is where a motor program comes into play." As I see it, even the corrections initiated on a closed-loop basis by the error servomechanism discussed first constitute an elementary form of motor program. At that level all that is formulated is how far to move in the next instant in time. As the level of environmental predictability increases, so does the complexity and extent of movement sequences that are formulated as Gestalts or integral units. In the discussion of tracking periodic signals the concept of a parameter comparator was introduced. It can be thought of as one mediator of higher-level temporal organization. When following sinusoidal signals the subject focuses his attention on monitoring and controlling amplitude, frequency, and phase of the sine wave pattern, rather than on the position to be at the next instant in time. Thus we might say he has automated the process at a lower level and the sine wave pattern corresponds to another level of motor program, but the more important point is that the subject has shifted his perspective concerning the level of organization at which he is working. He is simply solving a different problem at a new level. Piano playing and typing are skilled activities that can carry this concept of parameter control to very high levels of organization indeed.

Similarly it would be easy to argue that a schema instance, as defined here, represents a genuine motor program, but again I see that as merely another focus of attention and organization in which the goal to be achieved takes precedence over the stimulus situation. Rather than requiring the subject to conform to a rigid input sequence, he must instead formulate a motor act to accomplish a goal consistent with the stimulus conditions that exist at the time. As a function of practice the subject builds up more and more general schemata and higher-level goals on which to focus his attention and from which to evaluate success. One key to skill training is to provide knowledge of results consistent with the level of organization at which the subject is operating at each stage in the development of the skill.

The concept of a hierarchy of levels of organization in motor skills dates back to Bryan and Harter (1899) and their analysis of telegraphic signal transmission skills. It includes Book's (1908) work on typewriting and is captured effectively by Miller, Galanter, and Pribram (1960). These authors also emphasize the generality of the concept for virtually all kinds of behavior. The idea was further supported empirically in my doctoral thesis (Pew, 1966) in which subjects performed a task requiring rapid systematic alternation of key responses in order to control the movement of a target. Early in practice they responded point by point in time, waiting for the result from one response before initiating the next one. After several days of practice they began responding with much shorter interresponse times, and the pattern of their responses revealed the development among different subjects of two higher-level strategies, one of them a rather sophisticated temporal modulation strategy to promote more efficient performance. I infer from these subjects' performance, and I believe the result to be general, that they were not operating completely open-loop; they were not ignoring feedback in order to impose a structure on their skill but rather were using feedback to monitor and control their performance at a level removed from the representation of individual key strokes.

Proponents of the concept of a motor program appeal to the now popular evidence for triggered-off motor sequences in lower animals such as locusts (Wilson, 1972) or in the development of bird songs (Nottebohm, 1970). It is interesting that these results are consonant with the idea of a memory schema, a rather high level of sophistication in terms of the hierarchy of control levels I have described here, but at the same time they imply a nonadaptive rigid structure to the resultant program, which is only rarely observed in man. The human swallow reflex is the closest human equivalent. At the level of animal behavior, however, Tinbergen (1951) points out one example that is more consistent with the multilevel representation of skills:[4]

> The grey lag goose reacts to eggs that have rolled out of the nest by stretching the neck towards it, bringing the bill behind the egg and with careful balancing movements rolling it back into the nest. The innate releasing mechanism of this response reacts to relatively few sign stimuli; objects of very different shape and size, provided they have a rounded contour, release it. In spite of the balancing movements the bird sometimes loses control of the egg and then the egg slips sideways. In this case the egg-rolling movement does not always break off, but it may be completed, very much as if it were a vacuum activity. If this happens, the sideways balancing movements are absent. This indicates that the balancing movements are dependent on continuous stimulation from the egg, probably of a tactile nature, while the other component, a movement in the median plane, is not dependent on continuous stimulation but, once released, runs its full course [p. 84].

The stereotyped motion coaxing the egg back into the nest is representative of the nonadaptive program ususally associated with lower animals. However, the lateral balancing movements are not. It appears that they were sensitive to tactile response-produced feedback and are representative of the servo-level corrective control I have described in the early pages of this chapter. Here, then, is a clear example of multilevel control typical of human skilled performance manifest in the grey lag goose.

One definition of a motor program or "automation" of a movement sequence implies that "automation" releases the requirement for attention to the execution of a skilled act. This definition is operationalized in the form of a time-sharing paradigm in which one attempts to assess the change in attention requirements of the skill in question as it is being practiced by measuring the improvement in performance on a subsidiary task performed concurrently (Bahrick & Shelley, 1958). While this may be realistic for certain kinds of tasks for which adequate performance can be produced at restricted levels of control, I do not believe it to be a general result. Rather it seems likely that practice shifts the level of organization at which attention is focused, but does not in principle reduce the task demands. The piano player who is focusing on the level of emotional communication via his music may not show performance differences as reflected in measures of keying accuracy, but an extra task would surely influence his ability to communicate an emotional interpretation of his piece, as reflected by subtle shifts in the temporal or intonational structure of his performance.

Even at this level of a tracking task Pew and Wickens (Pew, 1974) found in the study of performance of repeated and nonrepeated sequences that the addition of a simple memory task produced an approximately equal increase in error score for the repeated and nonrepeated segments at three different points during a 16-hour period of practice, even though performance on the repeated segment was as much as 28% better than on its random counterpart.

Underlying this discussion of attention to various levels of a hierarchy of control processes is the tacit assumption that a subject's attentional capacity is limited and cannot be focused on several levels of control at once. While the fundamental information-processing assumption of a limited capacity channel has not been a central concept from which my discussion of skills has been derived, it should certainly be clear that the proposal of specific control loops leans heavily on the assumption that an individual cannot, or at least does not choose to, operate at all levels in parallel.

Many of the chapters that follow (see particularly Pachella, Chapter 2, Townsend, Chapter 4, and Kantowitz, Chapter 3) raise the question of whether in fact a model that assumes limited capacity is viable and, if so, in which information-processing stages that capacity limit imposes its constraint. An analysis of the attentional demands of the kinds of processes and control modes described here could prove to be a fruitful direction, leading to insights about the processes themselves, as it has been in understanding more standard information-processing stages such as stimulus encoding or response selection (Posner & Boies, 1971). Thus far, however, there is little to say about attention demands of movement control processes beyond Ells' (1969) analysis showing somewhat decreasing attention demand as a movement progresses and the possibility of a further involvement of attention in monitoring the result of a movement.

<u>A tempting synthesis</u>. The block diagrams of Figs. 8 and 9 have been presented separately because they are complicated enough as they are. While a great deal of detail remains to be worked out, the main thrust of this chapter is that there is nothing incompatible among the representations of inner-loop control, higher-order tracking control, and the formulation and execution of so-called voluntary movements.

Rather, as was noted at the beginning, we should think of a continuum of levels of control and feedback, that the signal comparator operates at different levels at different times, and can even operate at different levels at the same time. What we observe in human skilled behavior is the rich intermingling of these various levels of control as a function of the task demands, the state of learning of the subject, and the constraints imposed on the task and the subject by the environment. The job of the researcher is different, depending on the level of analysis in which he is interested, but a general theory of skill acquisition will only result from consideration of all the ramifications of this kind of multilevel process-oriented description of skilled performance.

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Footnotes

1 The writing of this chapter and some of the author's research reported herein were supported by the Advanced Research Projects Agency, United States Department of Defense, and monitored by the United States Air Force Office of Scientific Research, under Contract F44620-72-C-0019 with The University of Michigan's Human Performance Center. Other research reported herein was supported by NASA Contracts NASr-54-(06) and NSR-23-005-364 with the National Aeronautics and Space Administration. The author is grateful to R. G. Pachella and J. I. Laszlo, and to R. J. Jagacinski, A. Rose, C. D. Wickens, G. Rupp, and other students, for many helpful discussions and critiques from which this chapter emerged. Cogent reviews of the chapter draft were provided by S. W. Keele, R. A. Schmidt, B. H. Kantowitz, B. O'Neill, and E. Hunt.

2 A signal that varies randomly as a function of time cannot be described in terms of its repeating patterns because in principle every finite-length sample is different from every other sample. It is instead necessary to specify two average statistics that may be computed from any sample. One of these is the signal's amplitude distribution: the probability distribution that describes the relative likelihood that the signal will be at various distances away from some reference value. The second one is the power spectrum or power spectral density. Any random signal can be reproduced exactly by adding together an infinite sum of pure sinusoidal signals each having the proper frequency, amplitude, and time relation to

all the others. The power spectrum is an estimate of the average power (amplitude squared) at each frequency that would be requi in principle to reproduce a particular random signal. The shape and extent of the spectrum tells us a great deal about the effects of a signal that cannot be deduced by direct inspection of the waveform itself.

3 This representation was developed in discussion with J. I. Laszlo.

4 The author is indebted to R. J. Jagacinski for pointing out this example.

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