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SENSORY FEEDBACK MECHANISMS IN PERFORMANCE CONTROL:

WITH SPECIAL REFERENCE TO THE IDEO-MOTOR MECHANISM [1]

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Four interpretations of the manner in which sensory feedback may be involved in regulation of skilled performance are reviewed. For the serial chaining (SC) and closed-loop (CL) mechanisms, response selection is assumed to occur on the basis of peripheral feedback from preceding correct and incorrect responses, respectively; for the ideo-motor (IM) and fractional anticipatory goal response (r_G–s_G) mechanisms, it is assumed that a response's performance is directed by anticipatory representation of its own feedback or of feedback from the reaction to a goal to which the response leads, respectively. Among the conclusions of the review are (*a*) evidence for r_G–s_G as a mechanism for specific response selection, as opposed to generalized facilitation or inhibition of instrumental performance, is lacking; (*b*) the notion of a mechanism for comparison of actual feedback with images of desired feedback is not essential for explaining error-correction performance which is characteristic of CL; (*c*) despite severe criticism by twentieth century behaviorists, the limited available evidence is quite supportive of a contemporary version of IM; and (*d*) IM, SC, and CL can be regarded as serving complementary performance control functions—selection or "programing" of voluntary performance (IM), coordination of action within invariant sequential performances (SC), and coordination of action within sequential performances requiring correction responses to error stimuli (CL).

Analyses of the acquisition of skilled voluntary performance have frequently been formulated in terms of a transfer of performance control from situational stimuli to response feedback stimuli—that is, to interoceptive or exteroceptive stimuli produced by the learner's own behavior. This paper reviews four conceptions of the nature of sensory feedback mechanisms mediating voluntary performance, including serial chaining, closed-loop, and fractional anticipatory goal response mechanisms, and gives particular attention to a reformulation of the principle of ideo-motor action.

At the outset, certain boundaries of the present treatment should be marked off. First, verbal mediating mechanisms and the related topics of meaning and meaningfulness will not be given detailed coverage since it would expand this paper greatly, and perhaps unnecessarily, to attempt to do justice to the literature on verbal mediation. A number of influential writers (Goss, 1961; Luria, 1961; Miller & Dollard, 1941; Osgood, 1957; Pavlov, 1955) have assumed, as is assumed here, that verbal mediators of skilled performance differ from nonverbal mediators primarily in that the former operate at higher levels of performance organization. Accordingly, a

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later section of this paper briefly treats the application to verbal behavior of principles developed herein regarding nonverbal sensory feedback mediating mechanisms. Second, since the present focus will be on mediation processes in performance of learned skills, data and theorization concerning mediation in classical conditioning and concerning innately organized skills will not be considered. Third, no attempt will be made to be comprehensive in reviewing previous theoretical treatments of mediation involving sensory feedback. Major hypotheses will be discussed primarily in terms of the work of their principal advocates.[3] Finally, review of empirical literature regarding three of the formulations will be limited to two types of studies—those demonstrating the proposed sensory feedback mechanisms in operation and those indicating limitations on the applicability of the mechanism.[4] For the case of the ideo-motor mechanism, more detailed review will be given.

Notation

The following conventions of notation will be observed in describing and analyzing sensory feedback mechanisms. The capital letters, S and R, will designate overt sensory and motor events, respectively, as well as the central nervous system (CNS) processes that are active in conjunction with them. Lowercase letters, s and r, will designate hypothesized covert processes corresponding to (i.e., representative of) S and R, respectively. In addition to designating specific sensory and motor events, subscripts will be used to relate responses to their sensory feedback. In general, sensory feedback from a response will be indicated by a capital S connected to R by a solid line, with both letters having the same subscript, for example, R_A–S_A. A lowercase symbol bearing the same subscript, for example, s_A, will indicate a covert process representing this sensory feedback.

The term image, or more specifically ***response image,*** will be used in this review to refer to covert processes representative of sensory feedback from responses. It may be noted that this is possibly a narrower or different use of the term than might be employed by others.

Conditioned bonds will be represented by a pair of letters separated by a dashed line, the first designating a conditioned stimulus, the second a conditioned response. Although some theorists confine the stimulus and response categories to sensory and motor events, respectively, others allow sensory responses—that is, allow the representational sensory process in the response position of the conditioned bond (e.g., Birch & Bitterman, 1949) ; still others (e.g., Hebb, 1949) allow conditioned bonds totally within the motor system. Assumptions about the procedures necessary to establish conditioned bonds similarly vary in their restrictiveness. In the remainder of this review, the conditioning assumptions employed by various theorists will be introduced when appropriate for interpreting their hypotheses involving sensory feedback mechanisms for response selection.

Types of Sensory Feedback

Two types of sensory feedback, intrinsic and extrinsic, may be distinguished. Intrinsic feedback is that which will be received providing only that the organism's sensory pathways are functioning. For extrinsic feedback to be received, in contrast, there must be some additional external mechanism operating—such as the food delivery apparatus in a Skinner box, an experimenter

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[3] It may be noted that no coverage will be given to several relatively brief theoretical discussions that were not readily placed into one of the present four categories (e.g., Birch & Bitterman, 1949, p. 306; Hebb, 1949, pp. 155–157; Morgan, 1894, pp. 173–196; Pavlov, 1957, pp. 306–310). The reader interested in more detailed historical coverage of theorization concerning mediation by response-produced stimuli will find the review by Goss (1961) to be a useful source.

[4] Among other sources, the recent reviews by Adams (1968), Rescorla and Solomon (1967), and Taub and Berman (1968) have facilitated the present review. The reader seeking greater coverage of empirical literature pertinent to the serial chaining, fractional anticipatory goal response, and closed-loop formulations to be discussed should consult these sources. The recent appearance of *A Handbook of Contemporary Soviet Psychology* (Cole & Maltzman, 1969) has enabled inclusion of greater reference to the Russian literature than would otherwise have been possible.

delivering verbal reinforcements, the electrical circuit controlling conditioned stimulus termination in an avoidance task, etc. The intrinsic-extrinsic distinction has been made along similar lines previously by Annett and Kay (1957) and corresponds to the direct-indirect or topographic-nontopographic distinction employed by Taub, Bacon, and Berman (1965). Except where otherwise noted, the coverage of this review will be limited to intrinsic sensory feedback processes. Intrinsic feedback may be interoceptive, such as proprioception from movement, or exteroceptive, such as visual perception of movement and auditory perception of speech; thus, "intrinsic" should not be interpreted as equivalent to "internal" or "interoceptive." The author suspects that any generalizations made for intrinsic feedback processes would apply equally to extrinsic feedback, provided only that the response-extrinsic feedback contingency is comparably reliable to typical response-intrinsic feedback contingencies. However, establishment of this applicability would properly be the subject for a separate review.

SERIAL CHAINING

The simplest type of substitution of response-produced stimuli for situational stimuli in the control of movement is typified by learning to perform any routinized series of responses such as a musical melody. Correct performance may be described as a series of specific responses corresponding to the series of notes comprising the melody. At first, such performance may be guided by a series of situational stimuli such as the written notes of the melody or the notes as sung or played by a teacher. As performance becomes reliable, playing a given note is consistently preceded not only by reception of the situational stimulus to which performance is already conditioned, but also by reception of stimuli produced by performance of the preceding series of notes. The latter stimuli may be auditory, visual, proprioceptive, kinesthetic, and/or tactile; regardless of modality, they share the attribute of being directly contingent on the performer's own behavior—that is, they constitute intrinsic sensory feedback from performance. It follows from an assumption of conditioning by S–R contiguity that control of such skilled performance may readily be transferred from situational stimuli to intrinsic feedback stimuli. This process of sensory-feedback-based serial chaining of responses is schematized in Figure 1, which is similar to diagrams presented by James (1890a, p. 116), Watson (1930, p. 258), Hull (1930, p. 513), and others.

Evidence Relevant to Serial Chaining

A demonstration experiment for the serial chaining mechanism requires three steps: (*a*) the subject learns and practices a performance skill consisting of a sequence of responses, R_A, R_B, R_C . . . , originally under the control of the series of situational stimuli, S_1, S_2, S_3 . . . ; (*b*) the performance skill is tested under conditions of interruption of the sensory pathways for S_1, S_2, S_3 . . . , while leaving intact pathways for S_A, S_B, S_C . . . (intrinsic sensory feedback stimuli); and (*c*) the skill is again tested under interruption of pathways for both sets of stimuli. The purpose of this paradigm is to demonstrate that S_A, S_B, S_C . . . , while originally playing no role in control of the skilled performance, have acquired the ability to guide the performance. This result would take the form of superior performance during Step *b* than during *c*. (Performance during *a* may be superior to that during *b*, but this is irrelevant to the demonstration.) The author has been unable to discover any experiments with infrahuman subjects that correspond to this paradigm. This may be a consequence of the difficulty in specifying the stimuli that control original learning of the skill in Step *a*. For example, Honzik (1936) found that rats could employ vision, smell, and audition interchangeably in original learning of an elevated maze. The difficulty in identifying the modality controlling original performance is indicated in a different fashion by the work of Taub and Berman (1968), who found that blindfolded monkeys with bilateral forelimb deafferentation were able to use their forelimbs in a variety of purposeful performances. These investigators could identify no modality that was guiding such

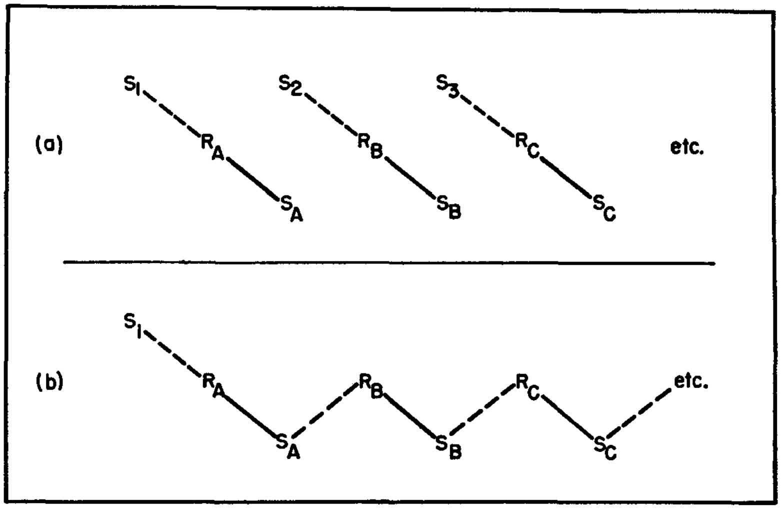

FIG. 1. Acquisition of serial chaining mechanism: The instrumental response sequence, R_A, R_B, R_C, etc., is originally guided by situational stimuli S_1, S_2, S_3, etc., and produces feedback stimuli, S_A, S_B S_C, etc. The figure shows (*a*) original separate links in response sequence and (*b*) the sequence coordinated as a result of conditioning of responses to feedback stimuli produced by preceding responses.

performance and suggested that the finding supported the hypothesis of *central efferent monitoring:*

> a purely central feedback system that could, in effect, return information concerning future movements to the CNS before the impulses that will produce these movements have reached the periphery. An animal could thus determine the general position of its limb in the absence of peripheral sensation [p. 188].

These observations (see also Festinger & Canon, 1965; Festinger, Ono, Burnham, & Bamber, 1967) should not be interpreted as implying that the serial chaining demonstration paradigm is impossible to achieve. In fact, Honzik's (1936) observation that proprioception, in the absence of vision, smell, hearing, and touch, was insufficient for rats' maze learning, provides the basis for implementing the paradigm. In Step *a,* the rats learn the maze; in Step *b,* vision, smell, hearing, and touch are obstructed; in Step *c,* proprioception is also eliminated. The finding that performance in *b* is superior to performance in *c* would stand as a demonstration of the serial chaining mechanism. Honzik felt it was clear that proprioception could play the role just outlined, although this conclusion was, as he acknowledged (Honzik, 1936, p. 86), not based on appropriate evidence.

In light of the status of the animal experimentation literature, the best demonstrations of serial chaining mechanisms come from observations of human behavior in performance of memory tasks. For example, in learning the words of a poem from printed copy, it is obvious that the original learning cannot occur without vision and, further, requires no supplementary modality (Step *a*). After practice, performance can occur with eyes closed or blindfolded (Step *b*). Finally, if asked to recite the *n*th line of the poem, the subject's latency will likely increase as a function of *n,* suggesting strongly that the subject is using time to provide himself with the stimuli of line $n - 1$ in order to be able to perform line *n.* This last task is presumed to correspond to Step *c* of the serial chaining demonstration paradigm—functioning to indicate the necessity of (overt or covert) response-produced stimuli—without going to the extreme of eliminating the sensory pathways involved.

Additionally, findings of disruption of overlearned performances such as speech, by elimination or alteration of feedback (e.g., Smith, 1966; Yates, 1963), strongly implicate the involvement of response-produced stimuli in the control of routinized sequential performances.

Finally, it seems fairly well established that the serial chaining mechanism is not always essential to the control of performance for which the originally controlling sensory modalities have been eliminated. The already-noted set of studies by Taub and his colleagues (Taub & Berman, 1964, 1968; Taub, Ellman, & Berman, 1966) indicate that monkeys can retain or relearn performance skills after deafferentation sufficiently extensive to interrupt any direct channel for conveying response-produced stimulus information to the CNS. Lashley (1951) and others have observed that highly skilled performances may occur too rapidly to warrant the assumption that stimuli produced by a given response might be effective in controlling the next response in sequence. It has been suggested, in consequence, that a well-practiced routinized performance may be learned in the form of a "motor program" that is capable of execution in the absence of feedback stimulus information (see the recent review of relevant evidence by Keele, 1968). This argument is well taken but should not be regarded as invalidating the type of serial chaining shown in Figure 1, since sensory-feedback-based chaining might be expected, nonetheless, to be of significance either as a state of transition to centrally organized motor programs or as a mechanism underlying performance of moderately learned skills requiring repetition of a standard series of movements.

FRACTIONAL ANTICIPATORY GOAL RESPONSES

The significance of serial chaining mediated by sensory feedback goes beyond enabling independence of routinized performances, once started, from extraorganismic stimulation. The added significance becomes apparent when it is allowed that instrumental response sequences can occur in attenuated forms that function chiefly to provide the performer with sensory feedback stimulation. Such attenuated response sequences (called "pure stimulus acts" by Hull, 1930) enable the performer to have *foresight*—that is, to anticipate the consequences of responses. Hull started with the serial chaining mechanism just outlined, added to this the idea that performance requiring a sequence of responses could be conditioned to stimuli (such as drive stimuli) that persist from the beginning to the end of the sequence, and combined these ideas to give a quantitative explanation of the dropping out of unnecessary responses (short-circuiting) in instrumental sequences. Hull (1931) took a significant further step, applying these same ideas to formulate the mediating role of sensory feedback from fractional anticipatory goal responses. Figure 2 schematizes the 1931 derivation, which was based on the assumption that fractional portions of the final, or goal response (R_G), in an instrumental sequence could short-circuit to the beginning of the sequence without disrupting the sequence. Accordingly, the series of responses could become conditioned to sensory feedback (s_G) from the fractional anticipatory goal response (r_G). With this derivation in hand, Hull was able to offer an explanation of *purpose* in terms of the habit concept; specifically, purpose could be equated with the ability to respond to a future goal event that is available as a stimulus in the form of sensory feedback from the anticipatory r_G. This was an improvement over the suggestion (Hull, 1930) that purpose could be embodied in the persisting drive stimulus, since the number of an organism's distinct purposes could be measured by the number of its goals rather than by the much smaller number of its drives (Hull, 1931, p. 497).

In the papers that developed the notion of mediation by sensory feedback from r_G, Hull (1930, 1931) used only a contiguity conditioning assumption. The emphasis on goal responses in these early papers was a forerunner of Hull's later postulation of the role of goal responses in primary reinforcement (Hull, 1952, p. 5) and secondary reinforcement (Hull, 1952, p. 14). In addition to providing sensory feedback to which responses early in the instrumental sequence

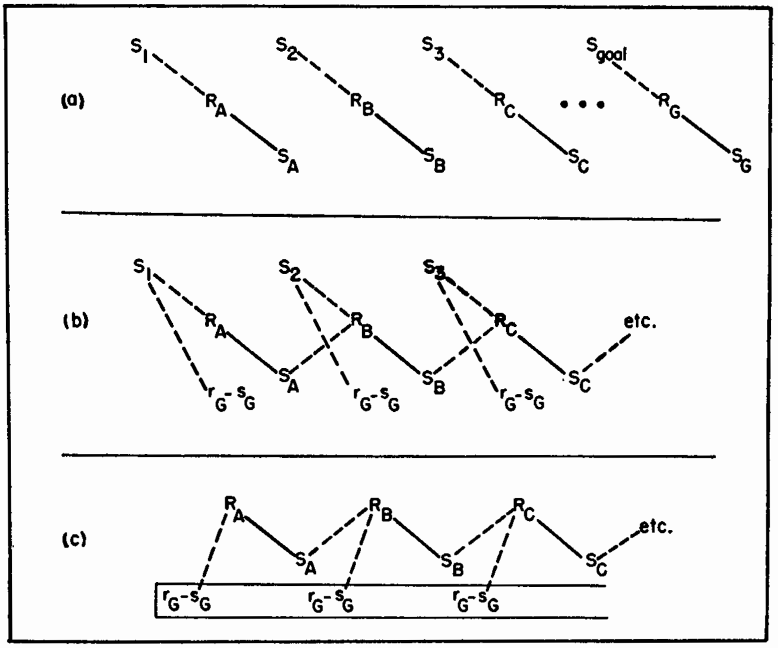

FIG. 2. Acquisition of r_G–s_G mechanism: (*a*) the instrumental sequence, R_A, R_B, R_G . . . , leads to a goal stimulus evoking response R_G; (*b*) fractional stimulus-producing portions of R_G become conditioned to S_1 and other stimuli directing the instrumental sequence; (*c*) fractional-goal-response-produced stimuli acquire discriminative control over the instrumental sequence, such that any stimulus capable of eliciting r_G can initiate the sequence. The simultaneous acquisition of a serial chaining mechanism is also shown in *b* and *c*.

could become conditioned, the r_G was assumed to reinforce stimulus-response connections throughout the sequence (Hull, 1952, pp. 150–153).

The fundamental insight in Hull's r_G–s_G analysis was the use of sensory feedback from an *anticipated* response as a mediator of performance. It will be recalled that the serial chaining mechanism employs sensory feedback from a *past* response as the performance mediator. Below, it will be observed that the ideo-motor interpretation of mediation involving sensory feedback from anticipated responses is derived using reasoning very much like Hull's, without restricting the application of this reasoning only to goal responses and their feedback.

Evidence Relevant to Mediation by r_G–s_G

The basic demonstration paradigm for mediation by fractional anticipatory goal responses consists of a test for transfer effects from a classical conditioning situation to an (already learned) instrumental response situation in which the unconditioned stimulus (UCS) of the former and the goal stimulus (S_{goal}) of the latter are the same. If r_G–s_G has acquired a mediating role for the instrumental response, then presentation of the classically conditioned stimulus (CS) should, by eliciting r_G in a vigorous form, facilitate performance of the instrumental response. A necessary control procedure is to repeat the experiment with different events as UCS and S_{goal}. The facilitation of the instrumental response by CS must be greater when UCS and S_{goal} are the same than when they are different, in order to rule out an explanation in terms of a general motivation-enhancing effect of CS as opposed to facilitation of specific responses conditioned to r_G–s_G.

A number of studies employing the classical-instrumental conditioning transfer paradigm have recently been reviewed by Rescorla and Solomon (1967; also see Trapold & Winokur, 1967). The results of these studies have been generally quite consistent with predictions based on assumed mediation by r_G–s_G for both appetitive and aversive UCS. However, a conclusion from these studies in favor of the r_G–s_G mediation hypothesis must be stated with some caution, since the control procedure of employing different events as UCS and S_{goal} has typically not been used. In relevant studies that did use different events for UCS and S_{goal}, LoLordo (1967) found strong facilitation of a shock (S_{goal}) avoidance response by a CS that had been paired with a different aversive event, loud noise (UCS); and Bower and Kaufman (1963) found facilitation of a water-reinforced bar-pressing response by a food-paired CS. These findings make quite tenable the speculation that classical-instrumental transfer effects represent nonspecific excitatory-inhibitory processes, rather than highly specific response selection mechanisms.

A few other findings indicate various limitations on the applicability of the principle of mediation by r_G–s_G to instrumental performance. Solomon and Turner (1962) demonstrated transfer of a shock avoidance response to a stimulus that had been paired with shock in a training procedure conducted while subjects (dogs) were skeletally paralyzed by d-tubocurarine. In order to account for such results, the r_G–s_G theorist is obliged to assume that r_G can be autonomic in locus, rather than skeletal, or perhaps that r_G need not occur peripherally at all. In the latter case, of course, it is no longer appropriate to talk about mediation by sensory feedback; rather some concept such as efference—that is, sensitivity to motor impulses—is required.

Warren and Bolles (1967) found that rats learned more easily to avoid front footshock than hind footshock, despite the fact that hind footshock produced an unconditioned response (lurching forward) topographically more compatible with the (running) avoidance response than that produced by front footshock (recoiling). If instrumental-response-compatible portions of responses to events such as electric shock do facilitate performance by short-circuiting to early portions of response sequences, as assumed in the derivation of r_G–s_G mediation, then it should have been easier to learn to avoid hind footshock than front footshock.

In summary, it is difficult to draw any firm conclusions about the validity of the proposed r_G–s_G analysis of sensory feedback involvement in response selection. Studies employing aversive conditioning situations provide particular difficulties for the r_G–s_G mechanism—indeed, Spence (1956, p. 164) has suggested that the r_G–s_G analysis may be inapplicable to aversive learning—while, even in the case of appetitive situations, the data seem fully compatible with an alternative interpretation appealing to nonspecific facilitative processes for explanation of observed classical-instrumental transfer effects.

CLOSED-LOOP MECHANISMS

A recently accelerating trend in the analysis of skilled performance is to regard the performer as an information processor who compares incoming sensory feedback from responses (reafference) with a stored representation of what feedback from correct performance should be (imaged reafference). Performance control is achieved by the information processor's detecting discrepancies between imaged and actual reafference, then generating responses that serve to reduce or eliminate these disparities. This closed-loop model, or servomechanism, is well known in engineering and was proposed as a comprehensive model for human behavior by Miller, Galanter, and Pribram (1960). Boring (1942) has traced the closed-loop model to the work of Bell (1826). A brief history of psychological applications of the closed-loop principle may be found in Miller et al. (1960, Ch. 3); a very recent review has been provided by Adams (1968). In addition, frequent references to acquired servomechanisms may be found in recent Russian literature (see chapters by Anokhin, Bernshtein, Feigenberg, Luria, E. N. Sokolov, and Zaporozhets in Cole & Maltzman, 1969).

It is interesting to note that psychological adaptations of the servomechanism principle have rarely included attempts to derive the mechanism from conditioning assumptions. Some writers have assumed the existence of *innate* behavioral servomechanisms and have attempted to formulate them in terms of the structure of nervous systems (see especially Holst, 1954); such discussions, of course, are tangential to the analysis of *acquired* skills that operate on servomechanistic principles. Mowrer (1960a), Anokhin (1961, 1969), Sheffield (1961), and Adams (1968) have discussed components of the necessary mechanism in terms of conditioning, but have left significant other portions unexplained. Smith (1966) has suggested that traditional conditioning principles are not applicable to the analysis of behavioral servomechanisms.

In Adams' (1968) formulation, it is assumed that sensory feedback stimuli from correct responses in skilled tasks leave "perceptual traces" which may later function as images to be compared with feedback from attempts to reproduce those responses.

> If a movement segment is recognized as correct [by matching an image] we go on to the next stage, but if it is incorrect an error signal is generated and we take corrective action in the hopes of finding a movement pattern that will be recognized as correct [Adams, 1968, p. 499].

Mowrer (1956, p. 126, 1960b, p. 283f.) proposed essentially a random generator of responses that continuously scans its response repertory, selectively facilitating incipient responses producing feedback matching that of previously rewarded responses. In Anokhin's (1961) more elaborate formulation, an "acceptor of action" mechanism serves to compare current response feedback with an anticipatory image of correct feedback; the detection of an error activates an orienting response as the first step in error correction.

These formulations must be considered "partial" conditioning analyses of closed-loop performance because, in each, the mechanism of error correction is not explicitly accounted for in conditioning terms. The position taken here, similar to that of Miller and Dollard (1941), is that it should be possible to do better than to appeal to random behavior or unspecified "corrective action" as the means of correcting errors. Rather, the period of extensive practice required to develop a performance skill should enable the performer to make fine discriminations of direction and extent of error and to learn appropriate correction responses based on these discriminations. Accordingly, it is proposed in Figure 3 that error information contained in the sensory feedback from a given response functions to select the subsequent response—the basic criterion for classification of the mechanism as "closed loop"—by virtue of *specific responses conditioned to specific error stimuli.* This error-correction mechanism is based on the assumption that closed-loop performance skills are typically acquired by practice with a correction procedure, such that a reinforced (i.e., correct) response is likely to occur immediately following an erroneous one. The reinforcement therefore serves to establish a conditioned bond between stimuli produced by the preceding error and the appropriate corrective action. The learner thereby acquires a repertory of corrective actions to specific error stimuli. Figure 3 also indicates a fundamental relatedness of closed-loop and serial chaining performances, with the closed-loop performance gradually acquiring the appearance of serial chaining as overall accuracy increases (see Figure 3h). It may be noted that the rotary pursuit task schematized in Figure 3 involves a predictable target motion; tracking tasks with unpredictable target motions should not be expected to eventuate in the serial chaining type of performance due to the nonrepetitiveness of their task stimuli.

A significant aspect of the Figure 3 account of closed-loop performance is its lack of reference to images or perceptual traces of response feedback. That is, if the Figure 3 elaboration of error-correction performance is accurate, feedback from current responding need not be supplemented by images of correct feedback in order to direct the selection of error-correcting responses. This seeming superfluousness of the response image is remarkable in light of the extent to which some closed-loop theorists (e.g.,

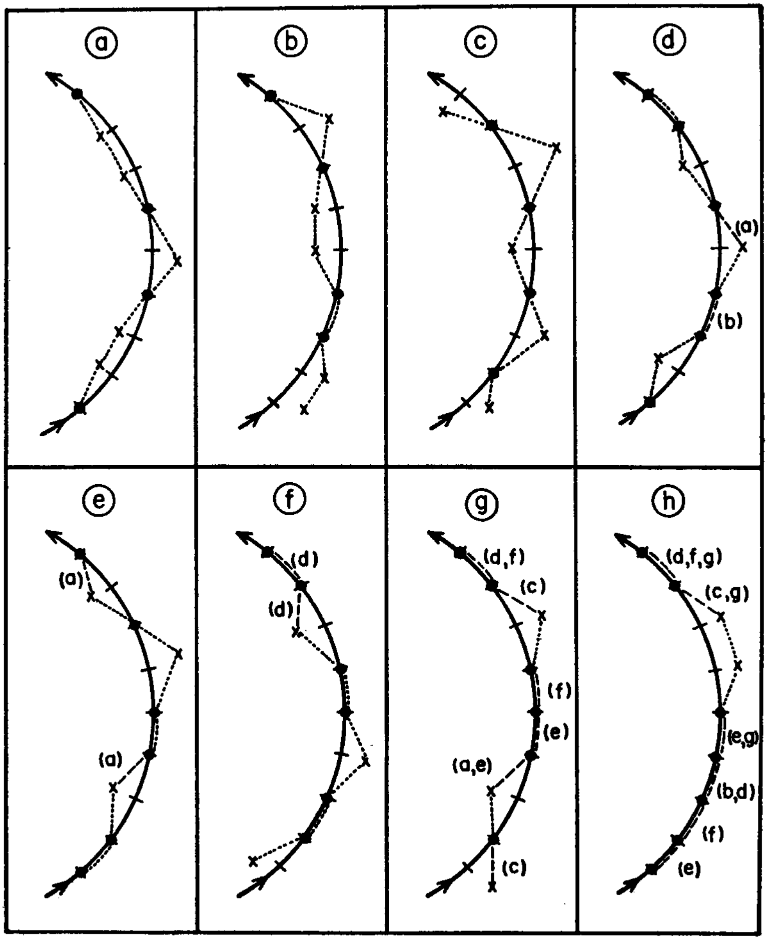

Fig. 3. Hypothetical acquisition of closed-loop performance. The task is a portion of a rotary pursuit problem subdivided into eight discrete segments for convenience of analysis. Arrows indicate direction of target movement; dot = on target response; x = off target response; dotted line = subject's trial-and-error performance; dashed line = correct response conditioned to stimuli of preceding correct or incorrect response with parenthetical indication of trials (a through h) on which conditioning occurred. Initial trial-and-error performance (Trials a–c) gradually changes (Trials d–f) to predominately conditioned performance (Trials g–h).

Adams, 1968; Miller et al., 1960) have stressed its importance in performance control. However, it will be argued below (p. 83) that there is a category of closed-loop performance for which response images are likely to be essential.

Evidence Relevant to the Closed-Loop Mechanism

The discussion of Figure 3 has suggested that response images may not be essential to closed-loop mechanisms. For this reason, and for the additional reason that the ideomotor formulation (to be presented next) also deals with response images, it is not clear that evidence concerning the role of response images in performance control is particularly crucial to appraisal of the closed-loop hypothesis. Nonetheless, some data dealing with response images will be considered in this section.

More relevant to demonstrating closed-loop mechanisms is evidence concerning the role of sensory feedback from current responses in performance control. Here the closed-loop interpretation provides predictions distinct from other sensory feedback mechanism conceptions. Specifically, the closed-loop hypothesis requires that feedback from *incorrect* responses be involved in the control of performance. This position may be clearly contrasted with the serial chaining hypothesis that feedback from *correct* responses is essential to the control of performance. Accordingly, the closed-loop hypothesis will be evaluated here primarily in terms of evidence concerning the importance of feedback from erroneous responses in the control of skilled performance.

Sensory feedback from erroneous responses. It is readily demonstrated that information provided by feedback from incorrect responses can be used for the purpose of improvement of performance and, further, that improvements achieved by means of providing error information will persist at least in part after reduction or elimination of this information (see references in Bilodeau, 1966, p. 272f.). As Bilodeau (1966, p. 258) has observed, however, it is often difficult to ascertain from empirical data whether the function of error information in improving performance is that of (*a*) providing essential stimuli for corrective responses, (*b*) motivating the subject's performance, or (*c*) reinforcing responses, or some combination of these.[5] Nonetheless, it does seem possible to make a good empirical case for the conditioning interpretation of closed-loop performance (Figure 3), which emphasizes the importance of the first and third of these functions of error information —that is, providing stimuli used for selection of (subsequent) correction responses and providing knowledge of results about the accuracy of preceding responses. (Nonconditioning interpretations of closed-loop performance would appear to be stressing the second function—motivation for corrective action—a function which, it may be noted, need not be denied by the present conditioning interpretation; cf. Miller & Dollard, 1941, p. 157.)

The most direct support for the conditioning interpretation of error-correction performance takes the form of indications that the ability to respond to error feedback with appropriate correction responses increases with reinforced practice in giving specific correction responses to specific errors. Nuttin and Greenwald (1968, p. 182) found that error corrections in a positioning task (blindfolded line drawing) markedly improved with practice. Taylor (1962, Ch. 9) found that adaptation to right-left visual reversal shows typical learning characteristics; specificially, adaptations to visual reversal on successive days show gradual reduction in extent of error. Smith (1966) found similar improvements as a function of practice in several tasks requiring performance under conditions of displaced visual feedback. Foley and Abel (1967), in contrast, failed to find evidence for improvement in adaptation as a function of practice when error feedback was not available on adaptation tests. Their negative finding nevertheless is consistent with the hypothesis that adaptation consists of learning specific correction responses to specific errors; that is, correction responses presumably could not occur in their task when the needed error stimuli were lacking. Additionally, a case study provided by Miller and Dollard (1941, Ch. 10) showed that learning to sing in tune involved gradual learning to correct erroneous attempts. Taken together, the findings just reviewed clearly support the conditioning interpretation of closed-loop performance presented in Figure 3. Behavioral

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[5] The paucity of research attention to the precise function of error information in improvement of performance may be due to the profound influence of Thorndike (e.g., 1932) on the direction of research into the effects of errors on performance. Thorndike felt that feedback from incorrect responses—most particularly the extrinsic feedback of punishment—was to be studied in terms of its effect on subsequent repetition of the punished response. This emphasis, which determined the course of research on punishment over a period of decades, directed attention away from interpretations of punishment as providing information that could be used to increase the probability of subsequent correct performance (cf. Nuttin & Greenwald, 1968).

servomechanisms, it may be concluded, can be acquired through practice resulting in the learning of specific correction responses to specific error feedback stimuli.

Response images. Observational learning studies (e.g., Bandura, 1965; Greenwald & Albert, 1968; Lumsdaine, 1961) have demonstrated marked facilitation of a variety of skilled performances directly following visual observation of another's performance. These findings are most directly interpreted as indicating that visual images of performance (i.e., representations of visual feedback from performance), acquired during the observation experience, subsequently facilitate the accurate control of performance. An alternative interpretation is that images of performance are coded verbally, with performance subsequently being controlled verbally (cf. Bandura, 1965, pp. 11–14; also Bandura, 1969, Ch. 3). However, the verbal coding hypothesis would seem insufficient to account for data indicating (*a*) substantial observational learning in young children who necessarily have limited verbal abilities (Bandura & Walters, 1963; Duncker, 1938; Zaporozhets, 1961), particularly the finding of delayed imitation by 16–18-month-olds (Piaget, 1951; Valentine, 1930), and (*b*) that the observer's visual perspective is an important determinant of transfer from observation to performance in a reaction-speed task (Greenwald & Albert, 1968). Further, even when observed performance is verbally encoded and stored, it remains possible that the verbal code may require decoding back to response images in order to be employed for successful performance control. In sum, there seems no reason to doubt that the availability of images of correct performance can markedly facilitate skilled performance.

At the moment, however, it seems unwarranted to assert that response images are *generally* necessary for closed-loop performance, even though they may be necessary in some cases. This judgment is arrived at not only through reasoning (see above, pp. 80–81) that response images have been hypothesized to contribute to a function that can be served by error feedback in the absence of images, but also through consideration of typical tasks that give evidence of closed-loop performance. In tasks such as pointing at a target, tracking a continuously moving object, or singing the same pitch that a teacher is singing, it is apparent that feedback information is *given* in the form of discrepancy from an external reference and requires no supplementary internal reference—the pointer and the tracker can see how far they are from their targets, while the singer can hear the interval between his and his teacher's pitch. In these cases an internal reference such as an image of the correct response is no more necessary for correct performance than is a child's knowledge of an object's location in a search game with "hot" and "cold" instructions. On the other hand, in cases of performance without an external reference, such as a musician giving a solo performance, it would appear that an internal reference is essential to appropriate self-correction of performance. Typically, skills requiring error-correction performance in the absence of an external reference are originally acquired with the aid of external reference stimuli (cf. Nuttin & Greenwald, 1968, pp. 183–184).

The most important conclusions to be derived from the present discussion of the closed-loop mechanism are that (*a*) it is reasonable to interpret behavioral servomechanisms as being acquired through stimulus-response conditioning in which specific correction responses are conditioned to feedback stimuli from specific erroneous responses, and (*b*) for a variety of learned performances with closed-loop characteristics (but not for all such performances) it is unnecessary to assume any important role of response images or other internalized reference processes.

IDEO-MOTOR MECHANISM

The principle that the perceptual image or idea of an action *initiates* performance of the action received distinguished support during the nineteenth century (James, 1890b; Lotze, 1852) but fell into disrepute in the twentieth century. The disrepute was likely a direct consequence of attacks on the ideo-motor principle published by some of the most influential American behavior theorists of the first half of the twentieth century (Hull, 1931; Thorndike, 1913; Watson, 1930). Examination of these attacks indicates that ideo-motor theory declined because (*a*) the psychological concept of *idea* (of a response or anything else) was not respectable in rigorous behavior theory (Thorndike, 1913; Watson, 1930), and (*b*) the ideo-motor principle, as stated by James (1890b, Ch. 26), was difficult to make compatible with conditioning analyses which accorded special functions to events such as goal reactions (Hull, 1931) or "satisfiers" (Thorndike, 1913).[6]

More recently, the concept of image and the assumption of contiguity as a sufficient basis for conditioning have regained respectability. Specifically, the notion of an idea or image of a response, conceived as a CNS representation of various modalities of sensory feedback from the response (cf. James, 1890b, pp. 488, 586), has been employed by closed-loop mechanism theorists such as Mowrer (1960a), Anokhin (1961), and Adams (1968; see also references mentioned by Adams, p. 496). Further, general treatments of the "image" concept have been given recently in physiological terms by Hebb (1968), Konorski (1967), and Beritashvilii (1969). The growing consensus opposing theoretical requirements for special reinforcing events as the cement holding together the conditioned bond may be seen in the recent writings of several former reinforcement theorists (Miller, 1963; Osgood, 1957; Spence, 1956) as well as in a variety of other learning-theoretical publications (Estes, 1959; Guthrie, 1959; Nuttin & Greenwald, 1968; Sheffield, 1961; Tolman, 1959; but cf. Landauer, 1969, for an exception to this trend).

Further indications of the establishment of a theoretical climate conducive to a reacceptance of the ideo-motor principle may be found in the following quotations:

> in his Principles of Psychology, published in 1890, in the chapter on "Will" (in Vol. II), William James . . . explicitly anticipated present-day developments. . . . perhaps the chapter's most remarkable feature is the extent to which the author makes sensory feedback from action essential to the continuation, and even initiation, thereof [Mowrer, 1960b, p. 284].

> James [clearly] saw the mechanism of voluntary movements, the mechanism at [sic] which he had arrived on the basis of astute introspection. It is most encouraging to know that we have come to exactly the same concept by quite different considerations—namely, through the physiological analysis of these movements [Konorski, 1967, p. 194].

> in and through all this system of Jamesian suggestions [about the "will"] is . . . the notion of ideo-motor action in which the central idea releases, triggers, gives life to, the waiting muscular system. How many times we hear today that our theories of learning do not tell us precisely how central functions, whether conceived in cerebral or in ideational terms, actually precipitate motor action! Yes, one reason is that we have forgotten James [Murphy, 1968].

A derivation of the ideo-motor mechanism, similar in several respects to that given by James (1890, pp. 579–592), is offered in Figure 4. The conditioning principle required for this derivation specifies contiguity as a sufficient basis for conditioning, and allows conditioning of *S–R, S–s,* and *s–R* bonds. In this derivation and the subsequent discussion, the terms "image" or "idea," as applied to responses, refer to central representations of sensory feedback from responses. Response images are reasonably regarded as somewhat abstract entities, representing functional response classes rather than specific instances of such classes. The degree of abstraction in a response image might be expected to increase with increases in the range of variability of the functionally equivalent responses it represents.

It would be possible to derive the ideomotor mechanism of Figure 4 without allow-

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[6] It is interesting to observe that Thorndike, an outstanding innovator in the use of experimental techniques to test psychological theories, was content to base his argument against ideo-motor theory on reasoning by analogy (e.g., "the idea of throwing a spear or of pinching one's ear, or of saying 'yes' tends to produce the act in question no more than the idea of a ten-dollar bill or of an earthquake tends to produce that object or event [Thorndike, 1913, p. 94]"), on a variety of introspective considerations (pp. 94–96), and on the results of an opinion poll of American Psychological Association members (pp. 97–105)!

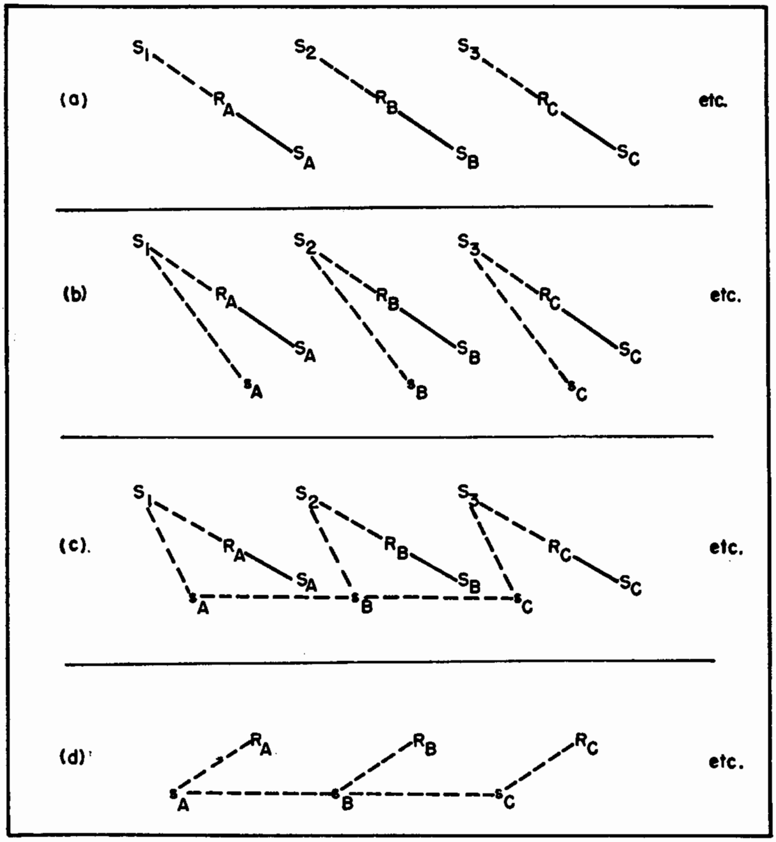

FIG. 4. Acquisition of ideo-motor mechanism: (a) repeated experiencing of S_1–R_A–S_A, S_2–R_B–S_B, etc., results in (b) conditioned anticipatory images of response feedback; these images may then (c) become anticipatory to actual performance, at which point (d) responses in the instrumental sequence can become conditioned to their anticipatory images, such that each element of the representative sequence, s_A–s_B–s_C etc., exerts discriminative control over its corresponding response.

ing S–s conditioning (e.g., the S_1–s_A bond) by using the device of having responses occur in anticipatory fractional form in order to make their anticipated reafference available for conditioning (cf. Figure 2). However, since this device would serve only as a means of preserving the principle of all conditioning being in terms of sensory-motor bonds—a principle that no longer seems to warrant preservation—and since such a device would also limit effective anticipated reafference to the proprioceptive modality, it has not been used in Figure 4.

It is interesting to observe that Hull (1931, pp. 500–503) felt he had fully accommodated the theoretical essence of James' ideo-motor conception by means of the fractional anticipatory goal response analysis. It is difficult to agree with this judgment, since Hull dispensed with the essential feature of James' analysis—namely, the principle that the idea of a response occurs in the form of anticipation of *its own* sensory consequences. Hull's analysis, instead, conceived the response idea as occurring in the form of anticipation of the sensory consequences of its ultimate goal response.

Ideo-Motor Mechanism versus Circular Reflex

The ideo-motor mechanism as presented here bears superficial similarity to the "circular reflex," a principle that received much attention in the first third of the twentieth century (e.g., Allport, 1924; Bok, 1917; Holt, 1931). The circular reflex principle refers to facilitated repetition of a response as a consequence of receipt of its own feedback stimulation. Observable phenomena that might be accounted for by such a process are ones involving persistent repetition of an action, such as the echolalic babbling of young children or the "nervous" repetitive tics of adults. In its most detailed statement (Holt, 1931, pp. 37ff.) the circular reflex has been treated as a learned mechanism, acquired through contiguity between feedback from a just-performed response and traces of the efferent impulses that produced the response. Among the serious difficulties of the circular reflex principle are (*a*) its failure to account for the occurrence of nonrepetitive actions or the cessation of repeated actions (cf. Miller & Dollard, 1941, Appendix A) and (*b*) the fact that it relies on a derivation involving backward conditioning (i.e., *S-R* conditioning from events occurring in the *R-S* order), a phenomenon that few learning theorists currently accept as valid (see Cautela, 1965, for a recent review).

The ideo-motor mechanism avoids the circular reflex mechanism's difficulty in explaining cessation of action by attributing a facilitatory function to the *image* of feedback from an action rather than to the feedback itself. Thus, only a simple ability to discriminate image from actual feedback is required to enable the organism to cease an action initiated by the former on reception of the latter. In regard to the backward conditioning assumption of the circular reflex derivation, it may be noted that only forward conditioning assumptions were used presently to derive the ideo-motor mechanism.

In sum, it would be inappropriate to lump the ideo-motor principle and the circular reflex formulation together simply because of their common concern with the involvement of feedback from a response in the facilitation of its own performance. The two mechanisms are derived from different assumptions and have different empirical consequences.

The Ideo-Motor Linkage

As derived in Figure 4, the ideo-motor mechanism is susceptible to a variety of interpretations regarding the processes linking response images to corresponding actions. At one extreme, it may be assumed that a response image will automatically evoke its corresponding action; alternatively, it is possible that one or more supplementary processes must operate in order for the image to be converted into action. That is, as in other theoretical analyses of behavior in which learning and performance are distinguished, it need not be regarded here that the existence of a learned ideo-motor connection is a sufficient condition for ideo-motor performance.

In his discussion of the ideo-motor concept, James (1890b) asserted:

> We may then lay it down for certain that every representation of a movement awakens in some degree the actual movement which is its object; and awakens it in a maximum degree whenever it is not kept from so doing by an antagonistic representation present simultaneously to the mind. . . . We do not have a sensation or a thought and then have to *add* something dynamic to it to get a movement. . . . Try to feel as if you were crooking your finger, whilst keeping it straight. In a minute, it will fairly tingle with the imaginary change of position; yet it will not sensibly move, because *its not really moving* is also a part of what you have in mind. Drop *this* idea, think of the movement purely and simply, with all breaks [sic] off; and presto! it takes place with no effort at all [pp. 526–527].

Eighty years later, the basis for describing the ideo-motor linkage is hardly more satisfactory than James' introspective observation. One category of relevant evidence comes from clinical observation of human patients suffering cortical brain lesions. The fact that cortical lesions can selectively impair ideational functions while leaving reflexive motor performance intact, or vice versa, indicates the existence of central nervous system locations at which the ideo-motor linkage may be broken. (Detailed reviews of the brain-damage literature may be found in Konorski, 1967, and Luria, 1966.)

A second category of relevant evidence comes from developmental investigations of voluntary regulation of performance. The most extensive research in this respect has been conducted by Luria (1961) and his colleagues, using an experimental technique developed by Ivanov-Smolensky (see Siebert, Nicholson, Carr-Harris, & Lubow, 1969). In Luria's experimental situation, a child squeezes an air-filled rubber ball in response to the experimenter's verbal instructions. The following developmental sequence, with approximate ages of initial appearance, has been abstracted from Luria's (1961) report:

1. (1½ years) The child can initiate responding to verbal instructions ("squeeze the ball"), if not engaged in another activity when the instruction is given, but does not inhibit ongoing responding when given the instruction "don't squeeze."
2. (2½ years) The child is able to respond to a delayed signal ("squeeze when the light goes on"). Once started, the response may be inhibited either by instructing the child to give a second response (move hand to knee), or by providing a distinctive exteroceptive signal contingent on the response ("squeeze to put the light out").
3. (3 years) With the aid of repeated verbal instructions accompanying each stimulus presentation, the child can squeeze to one signal (red light) and inhibit squeezing to a second (green light).
4. (3½ years) The child can use his own speech to initiate but not to inhibit responses. For example, he can give two successive squeezing responses to a delayed stimulus with the aid of saying "go! go!" on presentation of the stimulus. However, while he is able to learn to say "squeeze" to one stimulus and "don't squeeze" to a second, the latter self-instruction is more likely to disinhibit than to inhibit the squeezing response (i.e., the task is better performed if the child is asked to be silent for the second stimulus).
5. (5 years) The child becomes able to use his own speech to inhibit responding (the "squeeze–don't squeeze" experiment mentioned just above is successful), as well as to regulate performance at a variety of other complex tasks.
6. (5 years) At about the same time, the child also begins to be able to accomplish various complex tasks in silence, suggesting a transfer of behavior control from external to internal speech.

In this developmental sequence, the rather late appearance of successful inhibitory control of performance is consistent with James' assertion that a response image "awakens in some degree the actual movement which is its object" unless "kept from so doing by an antagonistic representation simultaneously present to the mind." It should be pointed out that Luria would likely oppose an interpretation of his experiments in terms of the ideo-motor mechanism (cf. Luria, 1966, p. 171). His own view (Luria, 1961, pp. 61–67) tends to follow Anokhin (1961) in regarding the closed-loop mechanism as the basis for voluntary control of performance. Nonetheless, Luria's findings remain quite amenable to an interpretation in terms of the child's increasing control, mediated verbally, over the link between response image and overt performance.

A final category of evidence relevant to the ideo-motor linkage consists of correlations between thoughts of movement and electromyogram (EMG) recordings of movement of the effectors. This technique was used notably by Jacobson (1932) and Max (1935, 1937) in their search for evidence supporting a "motor theory of thinking." The expected thought-EMG correlations were found, with Max's results being particularly impressive because of his careful procedures. Max used deaf-mute subjects and monitored EMG activity of their hands during dreams, with normals providing comparison data. The greater frequency of hand muscle potentials recorded during deaf-mutes' dreams was consistent with the expectation that their dreams would involve thoughts of hand movements (i.e., language). Findings of ideo-motor correlations in EMG data have subsequently been confirmed and elaborated by several Russian investigators (Bassin & Bein, 1961; Novikova, 1961; Sokolov, 1969). Jacobson and Max chose to interpret their results as supporting the hypothesis that peripheral movements were necessary for thinking. This hypothesis, however, has not stood up to more recent experimentation—particularly the finding that a human subject can have unimpaired perceptual and mental capacities despite extensive peripheral paralysis induced by the drug, d-tubocurarine (Smith, Brown, Toman, & Goodman, 1947). For the present, use of the results reported by Jacobson and Max will be limited to noting their consistency with James' view that the thought of a movement "awakens in some degree" the actual corresponding movement.

In summary, an exact formulation of the processes linking response images to overt performances is lacking. Much of the evidence is consistent with the hypothesis that an initial direct link between image and action is eventually brought successfully under inhibitory control—a conclusion that essentially preserves James' view on the matter (quoted above). Because of the definite evidence that humans, starting at age 2, if not earlier, are capable of some degree of voluntary inhibition of performance (see above summary of Luria's findings), it is obvious that evidence supporting the ideo-motor mechanism should not be expected to occur in the form of thought-of-action leading inevitably to performance-of-action. The question of just what form of data constitutes appropriate evidence for the ideo-motor mechanism is considered further in the next section.

Procedure for Testing Ideo-Motor Theory

An experimental demonstration of the ideo-motor principle requires two phases. In the training phase, a response (R_A) is practiced to a specific stimulus (S_1) and distinctive sensory consequences (S_A) are experienced following the response. The purpose of the second, or test, phase is to demonstrate that conditioning of R_A to s_A, as hypothesized in Figure 4, has occurred as a result of the S_1–R_A–S_A practice. This test requires the experimenter to be able to control presentation of S_A or some portion of it. For example, visual and auditory response consequences could be presented in part with the aid of audio and video recording equipment.

In the test phase of the ideo-motor demonstration experiment, performance of R_A on presentation of S_A alone, or S_A plus S_1, would be compared with corresponding performances of control subjects for whom R_A and S_A were unpaired in previous training. If the ideo-motor hypothesis is correct, performance by experimental subjects will be superior to (i.e., more accurate or more rapid than) that of controls. It is obvious in this paradigm that R_A must be a sufficiently difficult response so that there is room for measurable improvement in its latency or accuracy of performance in the tests with S_A. Further, the test organism must be highly motivated to perform R_A in response to the test stimuli, a requirement that is easily met with human subjects by use of appropriate verbal instructions.

Before consideration of relevant evidence, one aspect of the proposed demonstration paradigm must be considered further. The ideo-motor formulation deals with conditioning of responses to *central* representations of their sensory feedback; in contrast, the paradigm just outlined proposes to test ideo-motor theory by using portions of peripheral feedback stimuli to elicit the test response. The central-peripheral distinction is significant here since reception of peripheral reafference is typically the occasion for terminating, rather than initiating, the response that produces the reafference (see discussion of the circular reflex principle). Nevertheless, presentation of S_A in the suggested ideo-motor demonstration paradigm certainly should not inhibit performance of R_A by giving the subject an illusion that he has already performed it. For example, if a subject hears a tape recording of his voice, he will not believe that he is currently speaking; several components of the customary auditory and proprioceptive reafference from actual speech will be strikingly absent. In sum, the experimenter's presentation of a portion of S_A should function to facilitate selection of R_A, by generalization from assumed s_A–R_A conditioning (see Figure 4), while the presented portion of S_A will normally be sufficiently distinct from the complete reafference pattern from R_A so as not to be confused with the customary performance-termination signal.

Evidence Relevant to Ideo-Motor Theory

Anticipatory response images in performance control. Unlike the closed-loop formulation, there is no ambiguity in the ideo-motor formulation regarding the necessity of response images in response selection. Accordingly, the evidence already reviewed indicating facilitation of skilled performance by availability of response images (Bandura, 1965; Greenwald & Albert, 1968; Lumsdaine, 1961) may appropriately be cited in support of the ideo-motor formulation. As already noted, however, this evidence cannot decide between the closed-loop and ideo-motor interpretations of the role of response images in performance control. In the closed-loop formulation, the image may serve as a template for comparison with current feedback and need not be activated prior to performance, while the ideo-motor formulation requires the image to be active prior to performance for the purpose of initiating movement.

Clinical and anecdotal evidence. In his discussion of evidence bearing on ideo-motor theory, James presented interesting and suggestive evidence from clinical observations made by various investigators (James, 1890b, Ch. 26, especially pp. 489–492, 524–525). These observations, however, are compatible with a variety of formulations—not just the ideo-motor hypothesis. For example, in reviewing a report (by A. Strümpell) of the behavior of a child whose only intact senses were vision and audition, James noted the absence of skillful performance using the limbs when vision was prevented. Such observations are, of course, consistent with a variety of formulations in which sensory feedback plays a role in response selection, including the serial chaining and closed-loop formulations. More to the point of ideo-motor theory are observations such as those of Lotze (1852):

> The spectator accompanies the throwing of a billiard-ball, or the thrust of the swordsman, with slight movements of his arm; the untaught narrator tells his story with many gesticulations; the reader while absorbed in the perusal of a battle-scene feels a slight tension run through his muscular system, keeping time as it were with the actions he is reading of [quoted by James, 1890b, p. 525].

While observations such as these may be criticized as unsystematic and possibly biased, their likely accuracy is suggested by the reliable findings of correlations between thoughts of movement and implicit movement in EMG data (see p. 87, above).

Involvement of motor systems in perception. The hypothesis that perceptual processes involve a motor component has played an important role in a number of theories of perceptual development (Bruner, 1966; Hebb, 1949; Leont'ev, 1969; Nuttin & Greenwald, 1968; Osgood, 1953; Piaget, 1954; Sechenov, 1965; Taylor, 1962; Zaporozhets, 1969). In these theories, implicit movements are assumed to be evoked by stimulus objects as part of a perceptual process that precedes overt response performance—precisely the arrangement required, as schematized in Figure 4, to produce conditioning of overt performance to the covert representation. Among the "motor" theories of perception, those dealing with speech perception are particularly pertinent to the ideo-motor formulation; this is because stimuli produced by others' speech are highly similar to the feedback stimuli from one's own speech behavior. The conclusions of a recent review (Liberman, Cooper, Shankweiler, & Studdert-Kennedy, 1967) on this topic are as follows:

> Though we cannot exclude the possibility that a purely auditory decoder exists, we find it more plausible to assume that speech is perceived by processes that are also involved in its production. . . . there is typically a lack of correspondence between acoustic cue and perceived phoneme, and in all these cases it appears that perception mirrors articulation more closely than sound. . . . the listener uses the inconstant sound as a basis for finding his way back to the articulatory gestures that produced it . . . [pp. 452–453].

The mechanism required for this and related theories of speech perception involving the principle of *analysis by synthesis* (Halle

& Stevens, 1962) is one in which speech sounds, as auditory input, would link up with mechanisms involved in production of the same sounds. The ideo-motor mechanism fills this function exactly. In terms of the ideo-motor principle, it is assumed that auditory images of words are involved in the speech production process. The activation of these images by auditory input from others' speech could therefore serve as the required point of contact to speech production mechanisms. This would be a link between reception and production mechanisms that occurs centrally rather than peripherally, a feature that has been regarded as necessary by Liberman et al. (1967), and Neisser (1967, p. 218) in their recent analyses. (See, however, Lane, 1965, for a presentation of arguments opposing motor theories of speech perception.)

Electrical stimulation studies. Konorski (1967) recently has put forward the hypothesis that voluntary actions are organized and initiated in cortical kinesthetic centers that are also activated as a consequence of performance of the same actions. This view, as developed by Konorski, is a variant of the ideo-motor mechanism in which the kinesthetic aspect of response images is accorded an especially prominent role in response selection. The following quotation concerning typewriting performance is illustrative:

> when typewriting is performed under the guidance of acoustic or visual perceptions or appropriate images, the gnostic units [i.e., patterns of cortical activity] representing kinesthetic typing patterns of particular words are activated by association *before* the word is typed, and the motor performance is the result of this activation [Konorski, 1967, p. 191].

The evidence for Konorski's view is derived in part from studies indicating that the basic movements of mammals' skeletal musculature can be elicited by electrical stimulation of the same areas of the postcentral gyrus that serve kinesthetic functions for these movements (Penfield & Rasmussen, 1950; Woolsey, 1958). Such findings are consistent with Konorski's hypothesis that in the normal performance of voluntary movements, activity in kinesthetic centers precedes activity in efferent pathways.

Additionally, two types of procedures that have failed to produce reliable instrumental conditioning of skeletal movements have been cited by Konorski in support of his position. These include failures to instrumentalize rewarded movements produced by totally passive displacement of limbs (Kozak & Jankowska, unpublished, cited by Konorski, 1967) or by electrical stimulation of specified cortical areas (Tarnecki & Konorski, 1963). Konorski attributes these failures to a bypassing of the kinesthetic centers normally involved in voluntary movements—that is, bypassing of the kinesthetic ideo-motor mechanism presumably involved in all voluntary movement. Because few relevant studies have been reported, the conditions of instrumental conditioning failure remain to be established definitively; it would be premature to interpret the existing cases of conditioning failure as conclusive support for an ideo-motor mechanism. More detailed consideration of these data, together with discussions of relevant clinical evidence concerning behavior deficits of brain-lesion patients, is provided by Konorski (1967, especially Ch. 4 and 11).

Social facilitation. Some of the phenomena that have been labeled "social facilitation," for example the contagion of lighting up cigarettes in a group setting or the unintentional imitation of handwriting style in copying longhand literary passages (Starch, 1911), appear to involve an ideo-motor process. In his recent review, Wheeler (1966) observes:

> it is probably true that merely conceiving of a behavior increases its probability of occurrence and is usually the first step in performing that behavior. If there are no restraints present, observing and thus conceiving of a behavior is likely to lead step by step to performance [p. 182].

S–R compatibility in choice reaction time. In reaction time experiments, when different responses are required to each of *n* stimuli, reaction time may be observed to increase reliably as a function of *n*. This relationship tends to disappear, however, if stimuli and responses are "compatible," a condition that may be produced either by using overlearned stimulus-response relations, such as naming responses to familiar visual stimuli, or by having a simple spatial mapping of the different responses on the stimulus set, for example by having subjects respond to each of a row of lights by pressing buttons placed under each light. Under these conditions, reaction time is independent of n—that is, it remains approximately constant as n increases. The obvious interpretation of these findings (see Smith, 1967, for a review and discussion) is that the compatibility arrangement reduces to a minimum the time required for response selection, regardless of the number of stimuli. This conclusion is congenial to the ideo-motor principle, since it may be suggested that *S–R* compatibility facilitates response selection by minimizing the time required for access to an image of the correct response. This argument especially merits consideration in explaining effects of compatibility produced by spatial mapping of responses onto stimuli, since, in these cases, it seems unwarranted to claim that highly practiced stimulus-response relations are involved.

New evidence on choice reaction time. In some as-yet-unpublished research, the author[7] has pursued further the interpretation of *S–R* compatibility suggested in the preceding paragraph. Stimulus materials were visually or aurally presented letters and digits, with subjects having the task of responding as rapidly as possible by naming or copying the stimulus. If images of response feedback do mediate response selection via an ideo-motor mechanism, then speaking letters should be more compatible with (i.e., more rapid to) auditory than visual presentation of letter stimuli, while writing the letters should be more compatible with visual than auditory presentation. This prediction was based on the observation that, proprioception aside, the dominant feedback modality for spoken responses is audition, while for written responses vision would be the most important feedback modality. The prediction was confirmed at statistically significant levels, with the facilitative effect of stimuli being in the predicted compatible modality averaging between 17 and 44 milliseconds in five replications.

Summary of Evidence on the Ideo-Motor Mechanism

The preceding sections have reviewed a variety of evidence consistent with the basic principle of the ideo-motor mechanism—that an anticipatory image of feedback from an action participates in the selection and initiation of that action. Since data indicating greater accuracy of performance as a function of availability of response images may be interpreted also in terms of a closed-loop mechanism, the best evidence for the ideo-motor mechanism comes from studies in which responses occur with sufficient rapidity so as to render inapplicable the principle of error-correction on the basis of current feedback (cf. Keele & Posner, 1968). The inadequacy of the closed-loop mechanism for such cases has been indicated by Miller (1959, p. 250):

> Responses governed by proprioceptive feedback will necessarily be somewhat slow; in fact precise, delicate responses usually are relatively slow. But is this the sole mechanism, or is there some cruder, faster mechanism whereby responses of grossly different amplitude can be made without waiting for control of proprioceptive feedback?

The ideo-motor mechanism may be suggested as such a "faster" mechanism and, accordingly, it appears most appropriate to use reaction time procedures in tests of the ideo-motor mechanism. The chief difficulty with the reaction time studies that have been cited is the possibility that their results may be due to transfer from the subject's previously acquired repertory of associations that need not be of the ideo-motor variety. Transfer from previous learning is, of course, avoidable in principle by establishing novel, arbitrary response-feedback relations, giving the subject appropriate practice, then testing for response facilitation using the novel feedback stimuli as test stimuli in a reaction time procedure. A possible difficulty with this procedure may stem from the difficulty of new ideo-motor learning. Ideo-motor learning, as schematized in Figure 4, may quite reasonably be conceived as a process that

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[7] A. G. Greenwald. Demonstrations of ideo-motor effects. In preparation.

is based on thousands of learning experiences, spread over the early childhood years, for each of the body's basic voluntary movements—a process that may require, for example, many hours spent by a child in his crib viewing the movements of his hands, hearing the sounds of his voice, etc. If so, it may be inappropriate to expect that learning of novel ideo-motor connections may be observed with experimental training regimes involving even several hours of practice.

If attempts to form novel ideo-motor connections in the laboratory prove difficult, it may be more profitable to seek electrophysiological evidence for ideo-motor mechanisms. Promising new developments with the procedure of instrumentally conditioning movements elicited by cortical stimulation have been reported by Konorski (1967). It is to be hoped that the cortical stimulation experiments may eventually yield rather precise information concerning the role of cortical activity corresponding to response images in the process of response selection and initiation.

APPLICATIONS OF THE IDEO-MOTOR MECHANISM TO COMPLEX BEHAVIOR

In this section, very brief treatment will be given to suggestions concerning the role of ideo-motor mechanisms in complex human behavior.

Flexibility of Motor Performance

Bartlett (1932) has offered the following comment on the skilled stroke in an athletic performance:

> We may fancy that we are repeating a series of movements learned a long time before from a textbook or from a teacher. But motion study shows that in fact we build the stroke afresh on a basis of the immediately preceding balance of postures and the momentary needs of the game. Every time we make it, it has its own characteristics [p. 204].

How are such novel, skilled performances generated? This question is translated, with application of the ideo-motor mechanism, into that of how response images are arranged into novel sequences. The latter question, while straightforward, unfortunately lacks a psychologically satisfactory answer. Novel sequences of response images may be formed to a large extent through observation of others' performances and with the aid of verbal instruction (cf. Lumsdaine, 1961); however, it strains credulity to imagine that flexibility of human performance is limited to reproduction of novel inputs. It may be instructive, therefore, to consider the close relationship between the problem of explaining how response images are combined into novel sequences and another psychologically enigmatic problem—that of explaining how words are combined into novel sentences. The combination of basic movements into skilled action sequences may be likened to the combination of parts of speech into meaningful sentences (cf. Bruner, 1966, p. 10). For a golf swing—to take an example with which the author is familiar—the "parts" of action are such things as grip, stance, backswing, downswing, and follow-through. (These "parts" have subordinate components, of course, much as words have subordinate components at the phonemic and distinctive feature levels.) Just as sentences are meaningful only when the parts of speech are combined grammatically, the golf swing is skillful only if its parts are sequenced within certain formal restrictions. A skilled golfer may have a large repertory of stances, grips, backswings, etc., each conditioned to its own image, and will select an appropriate image from each of these categories in programing a swing appropriate to any given situation. Success may require a novel combination of the elementary movements, and it will certainly require them in a "grammatically" adequate form in which setting of the stance and grip precede the execution, in order, of backswing, downswing, and follow-through.

The terms "programing" or "planning" (cf. Miller et al., 1960) may serve to designate a stage in the preparation of complex performance at which response images are organized into an appropriate sequence. Berlyne (1965), in his analysis of "directed" thought processes, has given an analysis of such a programing process in which symbolic representations of successive subgoals in a problem-solving task are alternated with symbolic "transformations," that is, representations of actions that will lead from each subgoal to the next. The ideo-motor analysis fits readily with Berlyne's formulation if the symbolized subgoals of his analysis are understood as images of sensory feedback from the successive actions in the programed performance. The ideo-motor formulation provides a gain in parsimony over Berlyne's formulation by eliminating the need for his distinction between "transformational" and "situational" thoughts—that is, the distinction between symbolized responses and their symbolized consequences. This distinction becomes unnecessary because the ideo-motor analysis assumes that responses are represented in the form of images of their consequences, and that a sequence of such representations is sufficient for selecting the corresponding sequence of overt actions.

In order not to leave an undue impression of the accomplishments of the ideo-motor analysis, it must be noted that no solutions have been suggested for mechanistic problems of performance that might be classified as "motivational." In the analysis of complex performance, for example, no account has been offered of the processes that may be involved in selecting one sequence of images as a more useful program than another, or of processes involved in converting an image sequence into overt action once the programing process is completed.

An additional limitation of the present ideo-motor analysis has been the lack of consideration of the performance-controlling roles of symbolic processes other than response images. The class of verbal symbolic processes is especially demanding of attention. The following section indicates briefly the manner in which verbal processes can be integrated with ideo-motor mechanisms.

Verbal versus Response-Image Mediators of Performance

It has already been suggested that the ideo-motor mechanism may play an important verbal function, supplying the link between speech reception and production processes required in "analysis by synthesis" theories of speech perception (see above pp. 89–90). The present section will consider another aspect of verbal behavior in relation to the ideo-motor mechanism—specifically, verbal control of motor performance.

In the ideo-motor analysis of complex motor performance outlined just above, an extensive repertory of response images constitutes a "language" in which basic voluntary movements are represented. This view allows the verbal language to be regarded as a higher order system for symbolic representation of response images or combinations thereof. The variable sequencing of words allowed by the generative rules of the verbal language thus greatly multiplies the potentiality for performance flexibility already allowed by the lower order response-image language. This system of two orders of response "languages" may be likened to Pavlov's (1955) two systems of conditioned stimuli (signals). Pavlov's first signal system consists of conditioned stimulus-response associations for which the stimuli are nonverbal. In the second signal system, words represent stimuli of the first system and, thereby, enable control over any response conditioned to the first-system stimuli.

The second (verbal) response system proposed here may be regarded as an extension of Pavlov's second signal system conception. The Pavlovian view may be illustrated by reference to Osgood's (1957) example of the word "ball" as a symbolic mediator. As a mediator, "ball" is assumed to abstract the common properties of a variety of stimuli (tennis balls, baseballs, footballs, etc.) and to provide access to a family of ball-relevant responses (grasping, throwing, kicking, etc.). This example expresses the essence of Pavlov's second signal system concept, with "ball" serving simultaneously the functions of stimulus elaboration and response elicitation. The present view would introduce greater conceptual separation of these two functions. Specifically, "ball" would be regarded as a symbolic mediator on the stimulus side that makes accessible, with the aid of language processes, appropriate symbolic mediators on the response side (such as the words "grasp," "throw," "kick," etc.). These verbal response mediators would allow access to the corresponding actions, in accordance with the ideo-motor principle, by evoking appropriate lower order response image mediators. The present distinction between words with response-direction function and words with stimulus-elaboration function derives some support from the work of Luria (1961), who has been foremost in pursuing experimentally the implications of Pavlov's second signal system conception. Speaking of 18–24-month-old children who were given the instruction, "when you see the light squeeze the ball," Luria remarks:

> the words "when you see the light" produce direct orienting reactions in the child, who begins to look for the light signal; the words "squeeze the ball" produce direct motor reactions [i.e., in the absence of the stimulus light] [p. 55].

In this example, the distinction between words with stimulus function ("light," "ball") and those with response function ("see," "squeeze") seems most clear. As noted earlier, Luria would likely oppose the hypothesis that the word "squeeze" produces its motor effect by evoking a response image of squeezing. Nonetheless, his experimental observations remain compatible with this hypothesis.

Nonmediational analyses of performance control, that is, those specifying direct linking of responses to situational stimuli, have been criticized for conceptualizing a too-rigidly controlled organism. On the other hand, analyses that have dealt only with symbolic mediational processes are subject to the opposing criticism of too little control. That is, symbolic mediation constructs such as Osgood's (1953) mediating response, Hull's (1931, 1952) fractional anticipatory goal response, or Goss' (1955) verbal mediators have the characteristic of standing in a one-to-many relation to responses—each of these mediators is hypothesized to allow access to a variety or hierarchy of actions; further, any given action may be subsumed within the domains of several different symbolic mediators. Such high-level mediators are certainly necessary to account for human abilities to perform a variety of abstract functions, but are too abstract to offer a satisfactory account for the concrete process of selecting specific actions. The ideo-motor formulaton avoids this criticism by hypothesizing response image mediators that represent actions on a unique, one-to-one basis. It is for this reason that the distinction between higher order symbolic mediators and lower order response image mediators seems especially worth making. Because of the covert nature of either type of hypothesized mediator, substantial problems are faced by the investigator who wishes to demonstrate that a given performance is mediated by response images as opposed to higher symbolic mediators. As noted earlier, mediators at the response image level have been implicated with some clarity only in demonstrations of delayed imitation by very young children with limited verbal ability (Piaget, 1951; Valentine, 1930) and of the importance of observer's visual perspective in observational acquisition of a skilled performance (Greenwald & Albert, 1968).

SUMMARY AND CONCLUSIONS

Theory and evidence have been reviewed for four mechanistic conceptions of sensory feedback processes involved in performance control. The *serial chaining* mechanism provides for selection of responses within a routinized action sequence by stimuli produced as feedback from responses earlier in the sequence. Although relevant evidence from animal learning studies raises interpretive problems due to the difficulty of identifying the stimuli that control learning prior to the development of serial chaining, nonetheless there seems little reason to doubt that serial chaining is involved in performances characterized by invariant sequential routines. Further, it seems likely that the serial chaining mechanism can eventually be superseded for highly practiced routines by some form of neural motor coordination that operates without sensory feedback.

The *fractional anticipatory goal response* (r_G–s_G) mechanism is derived from the assumption that fractional components of responses to goal objects can short-circuit to early portions of instrumental response sequences. Despite substantial evidence for transfer effects from classical to instrumental conditioning situations, there is little basis for concluding that this transfer involves selection of specific instrumental responses by peripheral feedback stimuli from fractional goal responses. The available evidence is quite consistent with the alternative view that this transfer mechanism operates centrally rather than peripherally and involves general facilitation or inhibition of instrumental behavior rather than specific response selection. In the absence of evidence requiring interpretation of classical-instrumental transfer effects in terms of specific response selection processes, it seems appropriate to exclude the r_G–s_G mechanism from the class of sensory feedback mechanisms for response selection. Conceivably, further research could warrant reversal of this conclusion.

The formulation of a behavioral *closed-loop* mechanism, involving error-reduction mediated by comparison of current performance feedback with an image of desired feedback, derives a compelling quality from knowledge that sophisticated machines are readily designed to operate on such principles. Analysis of tasks requiring error-reduction responses suggests, however, that a comparison mechanism for actual versus desired feedback is no more a necessary component of learned behavioral servomechanisms than it is of mechanical servomechanisms. Specifically, it was noted that error information is frequently provided in the form of discrepancies from goals, particularly in visually guided performances; for these cases it is unnecessary to assume that images of correct feedback are involved in error-reduction performance. Review of evidence suggested that one principle that *is* generally characteristic of learned behavioral servomechanisms is the acquisition of a repertory of specific learned correction responses to specific error feedback stimuli. Remarkably, few psychological discussions of closed-loop performance have been formulated in terms of this principle of specific error stimulus-correction response learning, despite inclusion of this principle in one of the earliest treatments (Miller & Dollard, 1941).

Serial chaining and closed-loop mechanisms have in common the feature that a current response is selected on the basis of feedback stimuli from a preceding response. The essential difference between the two mechanisms is that the stimulus-producing response is a correct one for the serial chaining mechanism but an incorrect one for the closed-loop mechanism. For the *ideo-motor* mechanism, a fundamentally different state of affairs is proposed in which a current response is selected on the basis of its own *anticipated* sensory feedback. From an assumption of sensory-sensory conditioning, it can be deduced that an organism may representationally anticipate the sensory consequences of its actions; anticipated sensory feedback may thus become a discriminative signal for performance of the corresponding action. This derivation is essentially similar to one offered by James (1890b) and is based on assumptions that have recently achieved widespread adoption in psychological theory. The ideo-motor principle bears formal similarity to the r_G–s_G mechanism in that both involve response selection by a form of anticipated sensory feedback or reafference. The basic difference between the two mechanisms concerns the nature of the anticipated reafference that is postulated to be effective in response selection. For the r_G–s_G mechanism, the organism anticipates reafference from the goal response to which the instrumental action is leading, while for the ideo-motor mechanism the organism anticipates reafference from the instrumental action itself.

A broad variety of evidence was found to be consistent with predictions based on the ideo-motor mechanism, although feasible alternative explanations could be offered for many of these findings. Taken together, the varied alternative explanations are, of course, less parsimonious than the single ideo-motor formulation.

Complementary Processes in Performance Control

Three mechanisms for response selection involving sensory feedback processes have been identified. In two of these—the serial chaining and closed-loop mechanisms—feedback stimuli produced by peripheral movements serve response selection functions. In the ideo-motor mechanism, in contrast, response selection is achieved by central representations, or images, of sensory feedback. It may be proposed that the three mechanisms serve clearly distinguishable performance control functions. The serial chaining mechanism coordinates performance within routinized response sequences. The closed-loop mechanism serves a similar function for skilled performances that take place under nonconstant environmental conditions or that are of an order of difficulty such that an invariant response sequence would be inappropriate or unfeasible.

Both the serial chaining and closed-loop mechanisms are limited in that they do not account readily for the *initiation* of the performances they coordinate. For example, the serial chaining mechanism explains completion of the recitation of a memorized poem, once started, but does not explain initiation of that performance.[8] Action-initiation may be analyzed into components of response *selection* and response *execution*. The present formulation of the ideo-motor mechanism offers an account of the response-selection component of initiation by allowing anticipatory images of feedback from responses to serve the selection function. Additionally, the ideo-motor mechanism is adaptable to account for the role of ideational processes, at the response image or more abstract levels, in the planning of novel action sequences. The problem of explaining response execution within the present analysis has been set aside temporarily until a more precise formulation of the ideo-motor linkage is available (see above, p. 88). It may be suggested, however, that an account of CNS inhibitory-excitatory processes (e.g., Bindra, 1968; Glickman & Schiff, 1967) must be integrated with the ideo-motor formulation in order to account for the performance or nonperformance of actions for which images have been activated.

None of the mechanisms considered in this review is to be regarded as an invariable component of action. The performance of skilled actions after apparent total deafferentation of relevant feedback modalities (reviewed by Taub & Berman, 1968) or otherwise in the absence of feedback (reviewed by Keele, 1968) directly demonstrates the nonessentiality of serial chaining and closed-loop mechanisms for at least some performances. Similarly, it is reasonable to suppose the existence of a large class of skilled actions that are so automatically (involuntarily?) attached to their external stimuli as to render ideo-motor mediation unnecessary. As implied in the preceding sentence, this review has been leading to the conclusion that the ideo-motor mechanism is a basic mechanism of voluntary performance. It is tempting to suggest, although it would be difficult to know how to document the assertion, that the subjective experience of volition corresponds to the operation of an ideo-motor mechanism in which an image of response feedback precedes overt performance of an action. This view of the function of ideo-motor mechanisms provides a contrast with recent Russian literature (e.g., Anokhin, 1961; Bernshtein, 1969; Luria, 1961) in which the closed-loop mechanism is set forth as *the* basic mechanism of voluntary behavior, but is in essential agreement with William James' (1890b) analysis of voluntary behavior in his chapter on "Will."

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[8] Limitations of the closed-loop mechanism in accounting for initiation of performance have been acknowledged by some of the foremost closed-loop theorists; for example,

> How and where does the highly integrated process of forming a behavioral act occur? We do not yet have an answer to these questions which, in fact, have only been raised in recent years in great measure because of the influence of cybernetics [Anokhin, 1969, p. 845].

> Although the preceding sections of this chapter [on servomechanisms] may convey the impression that we are at last closing in on some of the most recalcitrant of psychological problems, there is no denying that sizable mysteries are still at large. One of these is the mystery of response initiation [Mowrer, 1960b, pp. 283–284].

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