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A CLOSED-LOOP THEORY OF MOTOR LEARNING[1,2]

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Following a discussion of the meaning of the term "skills" and a review of historical influences on their learning, a closed-loop theory for learning simple movements is presented. Empirical generalizations from the literature are stated, and the theory is used to explain them. The generalizations are of 2 classes: learning through the application of knowledge of results, and the effects of withdrawing knowledge of results.

Background of Skills and Their Learning

Sometimes the advancement of a scientific area can be slowed by ambiguities in an essential term, and this is the case for "skills" which encumbers the study of motor behavior. Uncertainty about the meaning of "skills" is of long standing. McGeoch (1927, 1929) had his doubts in 2 reviews of the acquisition of skill. McGeoch in the 1927 paper used Pear's definition of skill, which was an "integration of well-adjusted performances, rather than a tying together of mere habits." With this definition McGeoch accepted everything from letter cancellation to typewriting and language as skills, and diverse tasks such as these were covered in his review. In the 1929 paper, McGeoch still accepted Pear's definition of skill but now he had his doubts about it. He said that Pear's definition was so general as to lose its limiting values, and he observed that a proof of its vagueness was

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the wide variety of activities and topics investigated under the heading of skills. Pear's wide definition is still accepted by many, and without McGeoch's doubts, although some add the restriction that the study of skills should be restricted to highly successful performance (Cratty, 1967; Guthrie, 1952; Welford, 1968).

McGeoch never solved his problem, but it seemed that McGeoch wanted skilled behavior to have some complexity; it was not eyelid conditioning nor reaction time. Bartlett (1948) felt similarly, and he was more explicit than McGeoch. Indeed, Bartlett has been the most explicit of all. Bartlett wrote "perhaps the beginnings of skill are to be found in the graded response (p. 31)." He also said "...that such graded action, however simple it may be, has at least one of the fundamental marks of skill—an effector response is not merely set off by a receptor function but is guided and determined by it (p. 31)." Bartlett had a keen intuition when it came to analyzing skills, and here he was emphasizing the graded movement that is a part of virtually all skills and the feedback stimuli that control it.

The research on skills today is as many-sided as the definition of skills, about as McGeoch found it 50 years ago, with research being done on such diverse topics as sports, music, the factory, and military jobs. In their totality these fields can embrace a full span of human performance from lifting a finger to flying an airplane or delivering a speech. In experimental psychology, topics like conditioning, for example, started out with a well-defined subject matter and paradigm, and pursued a systematic search for variables, laws, and theory. Research on skills, by contrast, has studied anything that looks skillful to the common sense eye. If the study of verbal behavior had gone the same way, we would have journals filled with studies on how to learn and remember novels, billboards, and theater marquees. Compared to the study of skills, the histories of verbal behavior and conditioning over the same period is a scientific story to be envied. There are exceptions, of course, and the research on simple movements to be reviewed later on in this paper is prominent among them.

The villain that has robbed "skills" of its precision is applied research that investigates an activity to solve a particular problem, like kicking a football, flying an airplane, or operating a lathe. This accusation sounds more damaging than intended, because applied research is necessary when basic science lacks the answers. Nevertheless, the overall outcome of applied research is a collection of answers on specific problems, practically important to someone at a particular moment, but not the steady building of scientific knowledge that can some day have power to answer all the problems. Instead of starting with ideas about the laws and theory of movements and then finding the best situations in which to test them, investigators of skills have often started with tasks that looked skillful and, by studying them, hope to arrive at laws and theory. This approach is backwards for scientific productivity because it results in disconnected pockets of data that lack the unifying ideas that are general scientific principles. The task-centered approach is justified when practical reasons require us to know about tasks and efficiency in them, but it is a limited way of achieving the larger scientific goals of laws and theory.

Two conclusions emerge from all of this: First, let us forget about the term "skill" which has been so blunted by colloquial usage and research practice that it lacks scientific value. Second, a solid basic research effort is needed. The point of view of this paper is that we can most profitably focus on a common element of virtually all the behavior called "skilled." This common element, in agreement with Bartlett, is seen to be the graded response. If we are to build a science of skilled behavior we should begin with simple motor movements, and here we are at an advantage because our literature already contains a sizable array of data on simple, graded movements. The rest of this paper will dwell on theory and principles for the learning of simple movements, and the general history of research and theory on learning in the United States is a useful starting point.

Learning and learning theory is of strong interest in the United States, and a powerful influence on human learning has been E. L. Thorndike (e.g., 1949). Any discussion of learning, whether it is applied or basic, must pay its historical debt to Thorndike. In 1898, when the rest of psychology was concerned with the properties of consciousness and the association of ideas, Thorndike was doing objective, behavioristic work on animal learning. From this early work he stated his Law of Effect, which was a theoretical statement of rewarding and punishing events that determine learning. Thorndike was a man of wide interests, and as time went on he extended the use of his Law of Effect to human learning in the laboratory and the classroom. He studied both motor and verbal learning.

It is lengthy to review all of the ramifications of Thorndike's theorizing and the controversy that surrounded the Law of Effect (for a review and critique, see Hilgard & Bower, 1966, Chapter 2). Let it suffice to say that Thorndike's legacy to experimental psychology today is the Empirical Law of Effect, which says without theoretical rationale that the close following of a response by a rewarding event will lead to repetition of the response, and punishing events will lead to elimination of the response. Saying "Right" after a correct response is a rewarding event that will cause a human to acquire a desired response, and saying "Wrong" is a punishing event that causes an incorrect response to drop out. Such events can teach a child an arithmetic problem or proper social conduct. Or, a desired motor movement will evolve with the systematic application of "Right" and "Wrong." Food, water, and electric shock are among the events that produce learning in animals, and they are often called reinforcers. For humans, these kinds of events have also been called reinforcers, but very often they are called *knowledge of results* (KR).

Psychology's concern with reinforcement today is mostly atheoretical and empirical. An empirical approach does not seek underlying causes of behavior, content as it is with recording of observed regularities under a variety of conditions. The consistency in effects for reward and punishment are sought, whatever the rewards, the punishments, the tasks, and the organisms. In one sense this is a commendable search for generality, but in another sense it can be uncritical because it is easy to assume with this approach that common functions have common causes. Thus, if performance improves when the rat is reinforced with food, and performance improves when the human is reinforced with "Right," one is tempted to say that reinforcement works in the same way for rats and humans and that the laws of animal and human learning are the same. This may be so, of course, and we will have a simpler science if it is true, but it may be wrong also. Another consequence of this thinking is that students of human learning often do the same kind of experiments that animal psychologists do, such as delay of reward studies, partial reinforcement studies, and extinction manipulations. These experimental design practices are consistent with the thinking that humans and animals are covered by the same laws and that all we need do is run off the same paradigms as proof of it.

The Empirical Law of Effect is the cornerstone of S-R psychology, with generality and power, and it has never been seriously challenged. One should be cautious in the challenge with such an adversary, but nevertheless there are several lines of research which should make us impatient with the present state of affairs in human learning:

1. Delay of reinforcement in animals and humans does not work in the same way. Delay of reward for animals has a depressing effect on performance, but the evidence for humans shows little or no effect of delay at all.

2. The withdrawal of reinforcement has the well known extinction effect in animals and causes performance to decline. With humans the same phenomenon is sometimes found, but there is evidence to show that performance can remain the same when reinforcement is withdrawn, and possibly improve. Intuitively, we know this is so. The skill of the trained athlete does not disappear when the coach stops correcting him. His self-practice, without KR from the coach, can produce steady improvement just as if the coach were present.

3. Elwell and Grindley (1938) did several experiments on KR with different kinds of motor tasks, and in general they found their results on administering KR in acquisition and withdrawing it in extinction to correspond with animal work and the Law of Effect. However, they made the perceptive observation that a human *S* does not repeat rewarded responses, as animals seem to do. Rather, on the next trial he attempts to *correct his errors.* An unsuccessful movement results in *a variation* in the response just made, not its repetition. The Thorndikian, S-R interpretation requires a repetition of rewarded responses and avoidance of punished ones, but there is no accounting for improvement in performance based on systematic correction of error.

4. We all know that humans covertly guide their motor behavior with verbal responses (Adams, 1969a, pp. 490-494), at least in the early stages of learning. For example, we say to ourselves, "I'll make a shorter movement next time." That we talk to ourselves, form hypotheses, and instruct ourselves is a kind of covert guidance which fails to fit the S-R model that came from Thorndike and emphasizes the automatic, noncognitive nature of learning. The cognitive domain is the striking difference between man and lower animals, and it is hard to see laws of human learning without it.

5. The correctness or incorrectness of a motor movement, or any response for that matter, is known by the performer. One moves until he "knows" he is correct. Nothing in a S-R model covers this kind of behaving.

From these five problem areas can be distilled 3 broad points that are instructive for the general direction of any theory of motor learning. The first is that it should be a theory of verbal-motor learning, not just motor learning. There is a common belief that motor behavior is only a matter of movements, but this is a misconception. The human learning of a motor act involves, at certain stages, the influence of non-motor response classes. This assumes that response systems interact, and that the motor system is controllable by the verbal system. James (1890a, p. 114; 1890b, pp. 496-497) said that motor sequences are under conscious attention at the outset, or what today would be called verbal control, and that habit growth diminishes the conscious attention with which our acts are performed. Bernstein (1967, p. 136) also believes that consciousness drops out with practice and movements become automatic. James was on the right track in saying that verbal control is a variable early in motor learning and eventually drops out. Something like this must be so if verbal behavior controls motor behavior at all. It would be silly to postulate a theory where *all* motor behavior is under verbal control because words are crude when compared with the fineness of motor movements. The fingers of a concert violinist are not under verbal control, but they probably were in the beginning when he first started with his teacher.

The second point is that we need a revised conceptualization of how KR works. Typically, KR is taken to automatically inflict an increment of habit on the response it follows, which is the Thorndike tradition. However, if we accept the reasoning of Elwell and Grindley (1938), *S* is using KR to vary his response in order to reduce the previous error, which is cognitive activity not touched by an explanation that has KR a habit builder.

The third point is that we need new thinking about errors and human capability to detect and correct them. All of our learning theories treat errors incidentally. In one way or another, these theories have energizing agents for a response, like stimuli, habit, and motivation, and if an error occurs it is because a non-criterion response momentarily has a stronger composite of energizing agents. The sensing and using of error information is not a central feature of behavior for our contemporary theories, which means that they are open-loop, not closed-loop.

An *open-loop system* has no feedback or mechanisms for error regulation. The input events for a system exert their influence, the system effects its transformation on the input, and the system has an output. A poorly operating open-loop system (error) is because of characteristics of the input and/or the transformations imposed by the system. A traffic light with fixed timing snarls traffic when the load is heavy and impedes the flow when traffic is light. The system has no compensatory capability.

A *closed-loop system* has feedback, error detection, and error correction as key elements. There is a reference that specifies the desired value for the system, and the output of the system is fed back and compared to the reference for error detection and, if necessary, corrected. The automatic home furnace is a common example. The thermostat setting is the desired value, and the heat output of the furnace is fed back and compared against this reference. If there is a discrepancy the furnace cuts in or out until the error is zero. A closed-loop system is self-regulating by compensating for deviations from the reference.

Because open-loop notions dominate the psychology of learning today, and since closed-loop theory will be recommended eventually in this paper as a superior form, it will be instructive to examine the background and status of each in turn.

Open-Loop and Closed-Loop Accounts of Behavior

Open-Loop

Adams (1967, Chapter 10; 1968), and Adams and Bray (1970) have emphasized that learning and its theories of the past and today are primarily open-loop. If the stimuli are adequate, and the motivational and habit or perceptual states of the organism are sufficient, the response will occur, otherwise not. Regulatory adjustment of the organism by feedback from the response output is ordinarily not considered. There has been limited use of response-produced feedback, as in James' theory of serial action for highly learned "involuntary" movements (James, 1890a) which holds that movement patterns are acquired by the conditioning of each movement segment to the proprioceptive feedback of the preceding segment. Once started, the sequence runs off by the action of its own kinesthetic loops, and it is called the hypothesis of response chaining. Despite the emphasis on feedback, this theoretical idea is not truly closed-loop because it is not error-centered where feedback is compared against a reference mechanism as a basis for error detection and correction. For James, feedback acts as stimuli, and has no more theoretical status than an exteroceptive stimulus which starts the sequence, like a light on a display. The position is an open-loop variant, although some might see it as quasi-closed loop because of feedback. However viewed, it was the reaction to this line of thinking that led to a strengthening of a pure open-loop position and a putting down of feedback as a necessary variable for serial behavior. The research has various ramifications (for a review, see Adams, 1968), but the main point for this discussion is that Lashley was the one who articulated an unqualified open-loop theory of sequential behavior for psychology, with the first paper of a series being published over 50 years ago (Lashley, 1917).

The response chaining hypothesis emphasized proprioception and Lashley directly manipulated it by either cutting afferent nerves that carried proprioceptive feedback to the brain, or placing lesions in the cerebellum which is a governing center for movement (Lashley & Ball, 1929; Lashley & McCarthy, 1926). Rats were taught a maze before the operation and then relearned it afterwards. The outcome of these studies was that the animals had good postoperative success in the maze, even though motor coordination was poor. There was little resemblance of pre- and postoperative movements which the response chaining hypothesis would require, and Lashley concluded that the maze habit is centrally organized and runs off the sequence without proprioception. Deafferentation research that followed Lashley's, as well as other techniques like curare to deny proprioception during learning, generally found that proprioception is not a necessary ingrediant of learning. Lashley (1951) concluded that "...sensory factors play a minor part in regulating the intensity and duration of nervous discharge; that a series of movements is not a chain of sensory-motor reactions (p. 122)." Lashley's central emphasis with a disavowal of sensory feedback from the periphery is an open-loop conception. The central organization for the movement is most often called a motor program, although it also has been called a score (Weiss, 1950), or even a Victrola record (Hunter, 1930, p. 459).

The deafferentiation research is important for our understanding of feedback loops but it is not as decisive for the concept of the motor program as Lashley and those who followed his lead thought it to be. Good criterion performance without proprioceptive feedback is evidence against the response chaining hypothesis, but to prove a motor program it is necessary to show that learning can occur with *all* feedback loops eliminated. Lashley's rats could just as well have been guided by other sources of maze stimuli. Honzik (1936) showed that rats can navigate a maze by using various combinations of its several sense classes, and that so much of what we call skilled performance depends on the combination of feedback loops governing behavior. He criticized Lashley for not controlling other sensory cues well enough when he eliminated proprioception (Honzik, 1936, p. 58). Chase et al. (1961), Laszlo (1967a, 1967b), and Laszlo and Manning (1970), are more convincing in their argument for a motor program because they attempted to block all feedback channels for human motor acts and still found some competence remaining, but the most persuasive of all is Wilson's work on the locust. The use of a lower organism made for a thorough control and manipulation of feedback.

Man is not the only coordinated animal, and it is not surprising that biologists have been concerned about mechanisms of coordination in lower animals, such as the rhythmic patterning of a cockroach's legs, a fish's tail, or the wings of a locust. The issues are the same as at the human level: Is the movement sequence governed by a central motor program or does it depend on feedback from the response? Wilson studied sensory control of the locust's wings. The four wings can be started by loss of contact for the legs or pinching the abdomen, and it can be maintained by stimulating wind-sensitive hairs on the head with an air current. Sensors on the wings contribute to flight control primarily by sensing loss of lift and causing compensatory changes in the pitch of the wings. For experimenting, the organism is suspended in a controllable air stream.

It is Wilson's research on sensory reduction that led him to conclude for a motor program. The removal of whole wings, or portions of wings, had no effect on the patterning of movement for the remaining wings (Wilson, 1961), and this would not be expected if proprioceptive feedback was an influence on wing action. In this same study, Wilson reduced sensory feedback even more with preparations which had wings and legs removed, abdomen cut off, and wing sensory nerves cut. When the head was exposed to wind the muscle stumps of the wings contracted in a rhythmic, patterned way, just as in normal flight. The same rhythmic pulsation was found when direct recordings were made from motor nerves. The only possibility for proprioceptive feedback would be muscles in the head, and non-moving structures of the head and thorax. With even more extreme preparations where the head was removed, direct electrical stimulation of the nerve cord produced movements of the flight muscles which were sometimes coordinated normally when the parameters of stimulation were set to produce a spread of excitation in the neuron pool. In a further study, Wilson and Gettrup (1963) removed 2, 3, or 4 of the four proprioceptors (stretch receptors) at the base of each wing and found that wing frequency was reduced up to one-half of normal but coordinated movement remained. With all of these ways of eliminating sensory feedback, patterned organization of the wings persisted.

If motor neurons are dependent on peripheral feedback, then the timing of the stimulation should be important for producing a regulated output of the neurons. Wilson and Wyman (1965) stimulated the nerve cord with random inputs and made records of single unit muscle action potentials and direct observations of flight muscles. The output of the motor cell and the action of the flight muscles were found to be essentially as in normal flight. In a follow-up of Wilson and Gettrup (1963), Wilson and Wyman (1965) also varied the timing of electrical stimulation of the wing proprioceptors, but the phasing of the motor output was unchanged even though the overall frequency of the wings gradually changed, as if the input was being integrated. Timing of the output comes from the central neural organization itself, not the input.

Wilson (1964, 1966, 1968) concluded that there is a central program for wing movement, but this is not a naive open-loop position that dismisses sensory feedback. The motor output is not phase-coupled to the input, but the output does follow the input sluggishly after a lag, whether the stimuli are proprioceptive, light, sounds, changing body angle, or wind over the head or wing sensors (Waldron, 1961). Wilson hypothesized that the specific motor output is a genetically given program and that inputs have a widespread nonspecific effect on which performance importantly depends. Viewed in terms of biological adaptation, the ganglia have a pre-programmed normal motor pattern which input can modify to meet current needs. The nonspecific effect of stimuli is analogous to Hull's view of motivation as a general energizer or performance variable, not a local determiner of specific response units as habit would be (Hull, 1943).

What is the significance of this work on insect behavior for open-loop vs. closed-loop conceptions of motor learning? Foremost, the open-loop motor program is elevated as an explanatory device; it is biologically possible and now has more status than the speculative hypothesis it has been in psychology. But in accepting the feasibility of open-loop programs we must keep in mind that a genetic program for the locusts' wings does not mean that a *learned* response sequence has an acquired program that works in the same way. Wilson has feedback play a role in adaptation and, because learning is optimal adaptation, it may be that programs are trivial and feedback stimuli primary for learned motor behavior in humans.

Closed-loop

To qualify as closed-loop, a theory must be error-centered, with a reference mechanism against which feedback from the response is compared for the detection and correction of error, and the favorable climate for closed-loop learning theory has had influences from nonlearning sources. Engineering psychologists have been prominent in their attempts to use servo theory for the description of tracking behavior. Other influences on closed-loop learning theory were from experimental phonetics and medicine. Fairbanks (1954) devised a closed-loop model of speaking behavior which led to his work on delayed auditory feedback where verbal performance is impaired when auditory feedback is delayed a fraction of a second (Fairbanks, 1955). Chase (1965a, 1965b, 1965c), in the field of experimental medicine, presents a closed-loop block diagram where the peripheral feedback from a response returns to be processed centrally by an error detection unit. It is in the error detection unit that the sensory feedback is compared against a reference standard of correctness and, if a mismatch occurs, a change is transmitted to the effector system.

More direct and explicit closed-loop theorizing for learning has come from Russia in recent years (Anokhin, 1961, 1969; Sokolov, 1969) within the context of conditioning. The gist of the Russian position is that all impinging stimuli, whether they be environmental stimuli like the conditioned stimulus or feedback stimuli from the conditioned response, imprint what Anokhin calls the "acceptor of action," and what Sokolov calls the "neural model" or "image." This model develops as a function of trials or reinforcements, and its formation precedes the occurrence of the conditioned response. After the model has been formed the conditioned stimulus will arouse the model in anticipation of the response-to-be. When the response occurs, the stimulus feedback from the response matches the model, a successful behavioral sequence is observed, and *S* knows that a satisfactory action has been performed. But, if the stimuli fail to match the model, the orienting reflex, which was extinguished during the course of learning, re-appears in the presence of this error signal. The Russians see the orienting reflex as an investigating response that searches the environment, and it can be interpreted as the organism's attempt to eliminate the error.

Bernstein (1967) wrote similarly about motor behavior, Central to his closed-loop explanation is a motor command center defining what the response sequence should be. Feedback from the response enters a comparator where it is tested against the ideal one in the command center, and the result can be an error signal and a correction. Bernstein (1967, p. 133) has the image or neural model as the central command agent which defines the response that is fired and which is the reference against which feedback is tested for error. James (1890b, Chapter 26), in his discussion of voluntary movement, and Greenwald (1970) also use the image as the central representation which defines the response. Konorski (1967, Chapter 4) has a position like that of Bernstein's.

As commentary on the Russian work, the closed-loop or cybernetics emphasis in learning is commendable for our interest here. The neural model as the basis of error calculation is learned, and the learning is perceptual because the model is a function of sensory experience. What is troubling about some of the Russian work is that it does not distinguish between the mechanism for initiating the response and the model which evaluates the correctness of a response. Anokhin seems vague on this point, but Bernstein (1967, p. 130, Fig. 30) and Sokolov (1969, p. 682, Fig. 23-5) are clearer because they imply that the evaluation of feedback stimuli from the response is a comparison of feedback stimuli with the signals from the command center which initiates the response. The flaw in this approach is a failure to account for error detection, despite the concern with it. The model which defines and fires the response is also the mechanism for verifying it, so the response checks itself; the response and the model are necessarily congruent because the response is turned back upon itself. The agent that fires the response and the model that tests it must be different because without a difference we would not know that an error has occurred. We can make a verbal response like "Dog" and then hastily correct it by saying, "No, I mean Cat." The model verified that "Cat" is correct but something else insisted on "Dog." If the model was also the agent that fired the response, the response would have been "Cat" in the first place and the model would have verified it as correct.

The Theory

This section has a theory of motor learning, which uses some of the theoretical essentials from a closed-loop theory of verbal learning (Adams & Bray, 1970).

The theory strives for operationism so that its implications can be tested and thus, hopefully, avoids closed-loop principles as an interesting analogy. The frame of reference throughout is the instrumental learning of simple, self-paced, graded movements, like drawing a line, even though the implications extend further. And, the bounds include only learning by humans old enough to have a verbal capability.

The Nature of KR

Motor learning is best viewed as a problem to be solved, where *S* tries a movement, is given KR, tries again on the next trial, and so on, and the KR is the information used to solve the problem. Fundamentally, this point of view has Thorndikian roots because problem-solving tasks were widely used by Thorndike (Adams & Bray, 1970, pp. 391-393), such as a child having to discover the answer to an arithmetic problem by the application of "Right" and "Wrong," or a performer having to discover the movement required of him through the KR that he receives.

The KR is a function of error, and it can be of any precision. Broadly, KR can be classified as qualitative or quantitative. Qualitative KR is dichotomous, like the experimenter saying "Right" and "Wrong," or "Too long" and "Too short." Or an equipment analog of "Right" and "Wrong" might be used, like a green light for a correct response and a red light for an incorrect one, which the human could be expected to convert to verbal statements like *E* would deliver. Whatever is done, qualitative KR is gross and lacking in detail. Quantitative KR differs in the way of giving scaled numerical information, like "You moved 10 in. too far that time."

What kind of theoretical status should we give KR? The position taken here is that KR is foremost a source of information which results in corrections that eventually lead *S* to a correct response, rather than an automatic reward effect as Thorndike and those in his tradition would have it. The human is a verbally active organism, and we give him a problem to solve with the KR that we provide. The informational role of KR is primary, but a later section will discuss a motivational role also.

That KR is information to a problem-solving *S* means that *S* operates on KR and often will use it to form hypotheses and strategies rather than use the information in a direct fashion. If the KR is in meaningful units, like *E* saying "Your movement was 6 in.," *S*'s use of the KR will be direct because he knows a 6-in. movement reasonably well from past experience. However, if *E* said "Your movement was 6 long," *S* will have greater difficulty with the problem. He might try to discover what the units are and then produce a movement for 6 of them, or he may decide "6 long" was a large error and try to compensate accordingly on the next trial. If *E* said only "Wrong," *S* would have even less information and should produce even more elaborate and varied ideas about the correction to solve the problem. The point is that KR is often only a beginning point for *S*'s covert verbal behavior, and the verbal behavior that exerts influence on the motor act can be completely different from the KR itself. This position requires the premise that motor and verbal systems interact, which was mentioned before. The eventual recognition of these verbal influences on motor behavior will cause investigators to engage a new class of experimental procedures and designs, like verbal reports, the transfer of verbal responses to motor tasks, and individual differences in verbal abilities.

The Perceptual Trace

The choice of direction and the extent of movement are the two main properties of a simple, self-paced movement, and the latter will be dealt with first. To displace a limb in a motor learning situation requires a reference about past movements, information about error in the last movement (KR), and immediate feedback data on the momentary position of the responding limb. The reference is the memory of past movement, and so is fundamental for learning theory. This reference mechanism is often called the image, is what the Russians call the neural model, and what here is called a *perceptual trace.* It is the construct which fundamentally determines the extent of movement, and it is what *S* uses as the reference to adjust his next movement on the basis of the KR he has received. Beginning the movement brings an anticipatory arousal of the trace, and the feedback from the ongoing movement is compared with it. The strength of the trace grows as a positive function of experiencing the feedback stimuli on each trial; there is nothing to contradict the assumption that acquiring the perceptual trace is by stimulus contiguity.

Proprioception is an obvious source of feedback stimuli contributing to the perceptual trace, but tactual and pressure are sources of stimuli also. Sometimes movements have sounds associated with them. Many movements have visual sources of stimulus feedback, which could include changes in the visual surround as well as changes in the visual feedback from watching the responding limb itself. Here we are primarily concerned with the perceptual trace as it codes for self-paced limb displacement, but it may well encode for other dimensions of movement also. Sokolov (1969, p. 679) has hypothesized that response timing is coded in the trace.[3]

The concept of perceptual trace based on response-produced feedback stimuli is no more than an application of the notion of a trace or image which perception has used for a long time to account for the recognition of exteroceptive stimuli. The ability to recognize a picture seen yesterday is recognition based on the arousal and matching of a perceptual trace of the stimuli that was imprinted when the picture was originally seen. The same idea used for response-produced stimuli carries the implication that *S* can recognize a response which he has made before when their feedback stimuli arouse and match the perceptual trace laid down by them in previous experience. The theory makes the assumption that all impinging stimuli operate in the same way. Nature does not always practice economy, but if she does the gain in this case will be the linking of perception and body motion with a common principle.

The learning of motor movements is not as simple as acquiring a perceptual trace and matching current feedback stimuli to it. When *S* is making errors early in learning and his KR values are sizable, he is not responding on the basis of movements that he recognizes as having made before because this would cause him to repeat his past errors. For learning to occur, *S* must use KR to make the next response *different* from previous ones; he must use the perceptual trace *in relation to* KR from *E*, and adjust the response accordingly on the next trial. This early stage of motor learning, where corrections are based on KR and verbal transforms of it, is called the *Verbal-Motor Stage.*

The Verbal-Motor Stage comes to an end at an advanced stage of training where the error reported in KR has been acceptably small for some time, meaning that the correct response has been repeated for some time and its perceptual trace is strong. For continuing success at this advanced stage *S* need only recognize the present movement as having zero error when it matches its perceptual trace. *S* can now ignore KR because on a trial he continues his movement until it matches the perceptual trace and, when it does, he "knows" the response is correct. More than being able to ignore KR, *S* can now *learn without KR.* The specifications for the correct response are within him in the form of a strong per-

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[3] *The theory has the perceptual trace without a time dimension. To make the theory more testable, it was believed best to restrict the formulation to simple self-paced acts on which a substantial literature exists, and to enter variables like timing in the future. There is reason to believe that Sokolov is on the right track, however. Evidence indicates that the time-varying characteristics of proprioception contribute to movement timing (Schmidt, 1968, 1971 in press).*

ceptual trace and, in relying on it for the movement, he can make the correct response over and over and strengthen the perceptual trace even more. Learning under these circumstances has been called "subjective reinforcement" (Adams, 1967, pp. 295-302; Adams & Bray, 1970, p. 372). This final stage, where KR can be dropped out, is called the *Motor Stage,* and in passing to it from the Verbal-Motor Stage there is agreement with William James that "conscious" behavior eventually becomes "automatic."

One final word on the perceptual trace. It is convenient to refer to it as a single state, but in actuality it is a complex distribution of traces in a learning situation that has a series of trials. The movement on each trial lays down a trace, and this trace weakens as forgetting processes operate. The composite of old and new traces is the distribution. On any particular trial the response is to a dominant mode of the distribution. In the Verbal-Motor Stage, when only a few responses have been made and rather rapid short-term forgetting is occurring for each, the distribution is vague and KR is being used to adjust the response length with respect to an uncertain reference. The relatively large errors early in learning are undoubtedly a function of this indistinct reference, although the fact that learning occurs shows that the distribution is not all that vague ordinarily. As learning progresses to the Motor Stage, the distribution develops a prominent modal value defining the correct response length because the correct response or close approximations to it have been made a number of times, making the mode distinctive and relatively resistant to forgetting processes. Movement with respect to the mode in the Motor Stage yields rather accurate performance.

The Memory Trace

The theory relies heavily on the perceptual trace for the moment-to-moment guidance of behavior, and there is temptation to use the perceptual trace as the single controlling mechanism. This simplistic approach is rejected, however, in favor of a 2-state theory that has a second main construct called the *memory trace* whose role is to select and initiate the response, preceding the use of the perceptual trace. The memory trace must be cued to action, and the strength of it grows as a function of practice trials. Strength is a function of stimulus-response contiguity.

The reasons for the memory trace are three:

1. The use of one mechanism to command a response and to also test its correctness was criticized in the review of Russian closed-loop theory because it failed to account for error detection. If the agent that fires the response also is the reference against which the response is tested for correctness, the response

must necessarily be judged correct because it is compared against itself. Response activation and evaluation require independent mechanisms.

2. Use of the perceptual trace requires feedback, which occurs after the response begins. Something else besides the perceptual trace is required to fire the response in the first place. In effect, the memory trace is an open-loop motor program because it operates without feedback. As defined here, a memory trace is a modest motor program that only chooses and initiates the response rather than controlling a longer sequence, as advocates of motor programs usually imply.

3. Recall is response production and recognition is identification of a stimulus or a response. Adams and Bray (1970) and Kintsch (1970) have mustered lines of evidence to show that recall and recognition of verbal materials are based on two memory states rather than one. The S-R point of view has one habit state which all response measures reflect with different sensitivities. The evidence from verbal learning however, shows that recall and recognition are not functions of the same variables but can be separately manipulated and have distinctly different functional forms; it is one thing to recall a response and another to recognize an event. Pursuing parsimony and generalizing from the verbal data, it is assumed that recall and recognition are two different processes inherent in the single motor movement. The starting of the movement is motor recall, and it is based on the memory trace. Knowing whether the movement is proceeding correctly or not is a matter of response recognition, and the perceptual trace along with ongoing feedback govern it.

The memory trace and the perceptual trace seem confounded because they are both a function of practice trials and thus defy independent manipulation. This is only superficially so. While trials is a variable common to both traces, the perceptual trace is a function of impinging feedback stimuli which can be varied. For example, the detail and brightness of visual stimuli associated with movement could be manipulated, proprioceptive stimuli could be varied by the spring tension on a control, and the sounds associated with the movement could be enriched, amplified, or eliminated. Adams, McIntyre, and Thorsheim (1969) affected short-term verbal recall predictably by attenuating the feedback from verbal responses. Moreover, the memory trace applies only to the selection and initiation of the movement, while the perceptual trace governs movement extent. The variables for response choice can be studied independently of response length.

The literature on the learning of simple movements with which we are concerned concentrates on learning the length of a movement, and KR is information about error in length. Customarily in these studies, response choice is eliminated as a variable by having movement along a fixed track, so only KR about length is required. However, if a more complex task were to be used with choice of path a variable, then KR could be given about error in path selection along with extent of movement, and what has been said about KR and perceptual trace also applies to KR and memory trace. Knowing which highway to take is as important as the distance to travel on it.

Subjective Confidence

In verbal learning a confidence rating measure will show a subject's low confidence in the correctness of errors and high confidence in correct response (Adams & Bray, 1970), indicating that accuracy of responding can be accurately appraised. Theoretically, a confidence rating for a verbal response has been seen as reflecting the discrepancy between feedback stimuli from the response and the perceptual trace, with the smaller the discrepancy the higher the confidence. The same can be expected of motor responses, sometimes. If the motor response is a ballistic one like reaction time, the response is fired by the memory trace and is over before *S* can adjust his response during its course by reflecting its feedback against the perceptual trace. The post-response interval, however, has the elements of feedback stimuli and perceptual trace together for the appraisal of response correctness and the correction of error if it has occurred. Rabbitt (1967, 1968) has shown the correction of errors in choice reaction time to be accurate, as has West (1967) for errors in high-speed typing. But the story is different for the unhurried self-paced response. After the memory trace has started the movement *S* will always maintain a no-error congruence between feedback stimuli and the perceptual trace until near the end of the movement where, in the Verbal-Motor Stage, he will seek a mismatch to correct the perceptual trace by an amount based on KR. In the Motor Stage, where KR has been acceptably small, *S* will seek a full match of the perceptual trace throughout because he knows that it will bring him successful performance. Whatever the stage, *S* is subjectively confident of his performance because he is maintaining a no-error state throughout. Even the deliberate mismatch based on KR contributes to the feeling of confidence because *S* is doing it to eliminate error in the previous response. Thus, confidence ratings will be high whether objective error in the form of KR is low or high, although not necessarily the same irrespective of conditions because certainly *S* should show more confidence with a strong perceptual trace. Nevertheless, the expectation should be a considerable independence of objective error and judged error. If *S* were to be asked his estimate of error before KR was delivered, the error should run uniformly low and be poorly related to objective error.

Forgetting

Memory trace, perceptual trace, and KR each can be forgotten. Forgetting of the memory trace can be revealed in an inability to select the correct path for the response when choice is a variable in the task. The forgetting of the perceptual trace is more critical, considering the stronger role assigned to it for motor guidance, and its weakening should have a more damaging effect on proficiency. The KR is a verbal event which *S* undoubtedly repeats covertly, and thus some verbal learning accompanies the motor learning. A test of the verbal learning could be made by asking for recall of KR after a retention interval, as in the usual verbal short-term memory experiment. The forgetting of KR from the time of its delivery to its use on the next trial, which is possible when the post-KR interval is long enough, is a potential variable for the motor response. However, the time intervals in motor learning studies customarily have nothing to prevent covert verbal rehearsal and response strengthening, so the forgetting of KR should be slight. A properly constructed experiment should show KR forgetting, however.

Motivation

Adams and Bray (1970, p. 396) have interpreted the closed-loop theories of Sokolov (1969) and Anokhin (1969, p. 851) to mean that error is motivating, and they have adopted the same position for verbal error. Of course, there is more to motivation than error, but closed-loop theory has error as its focus and it has the special hypothesis that error is motivating. In the earlier section on subjective confidence it was pointed out that a self-paced response differs from a ballistic one because *S* has no subjective perception of error as he responds. But this does not mean that error-based motivation is absent in self-paced tasks. Rather, in self-paced tasks, the error information comes from objective sources in the form of KR, and KR is a source of motivation just like subjective error. Locke, Cartledge, and Koeppel (1968) have reviewed evidence showing that KR is motivating.

Acquisition

This section and the next are an exercise in theory applications. This section will be on *acquisition,* or those trials on which KR is administered. The behavior being analyzed is a self-paced positioning response, like drawing a line or positioning a lever. The line-drawing task comes to us from Thorndike, and the positioning of a lever is a mechanical variation of it. Of all the data in motor learning, that from simple tasks represent the most systematic body of knowledge and are best suited for theorizing. Principles derived from simple tasks may also apply to complex tasks. There is no necessity of interactions with task complexity.

Visual stimuli are experimentally eliminated in these tasks as they are ordinarily used, which means that a perceptual trace based on proprioceptive stimuli is probably dominant, although auditory cues from control action are usually present. Why students of simple movements have left the visual channel virtually untouched is a mystery. Perhaps they felt that a visual task would be very easy, which often would be true, but then the potency of visual feedback is a fact to be explained.

The *Verbal-Motor Stage* of learning will be under discussion in this section, where degree of learning is modest. The advanced *Motor Stage* at a high degree of learning will be discussed in the next section on KR withdrawal. The presentation of empirical data will be in the form of generalizations which usually will have several studies in support of them.

The kind of situation under discussion is movement, KR, movement, KR, etc., which is the standard acquisition paradigm. These events, and the intervals between them, are shown in Fig. 1.

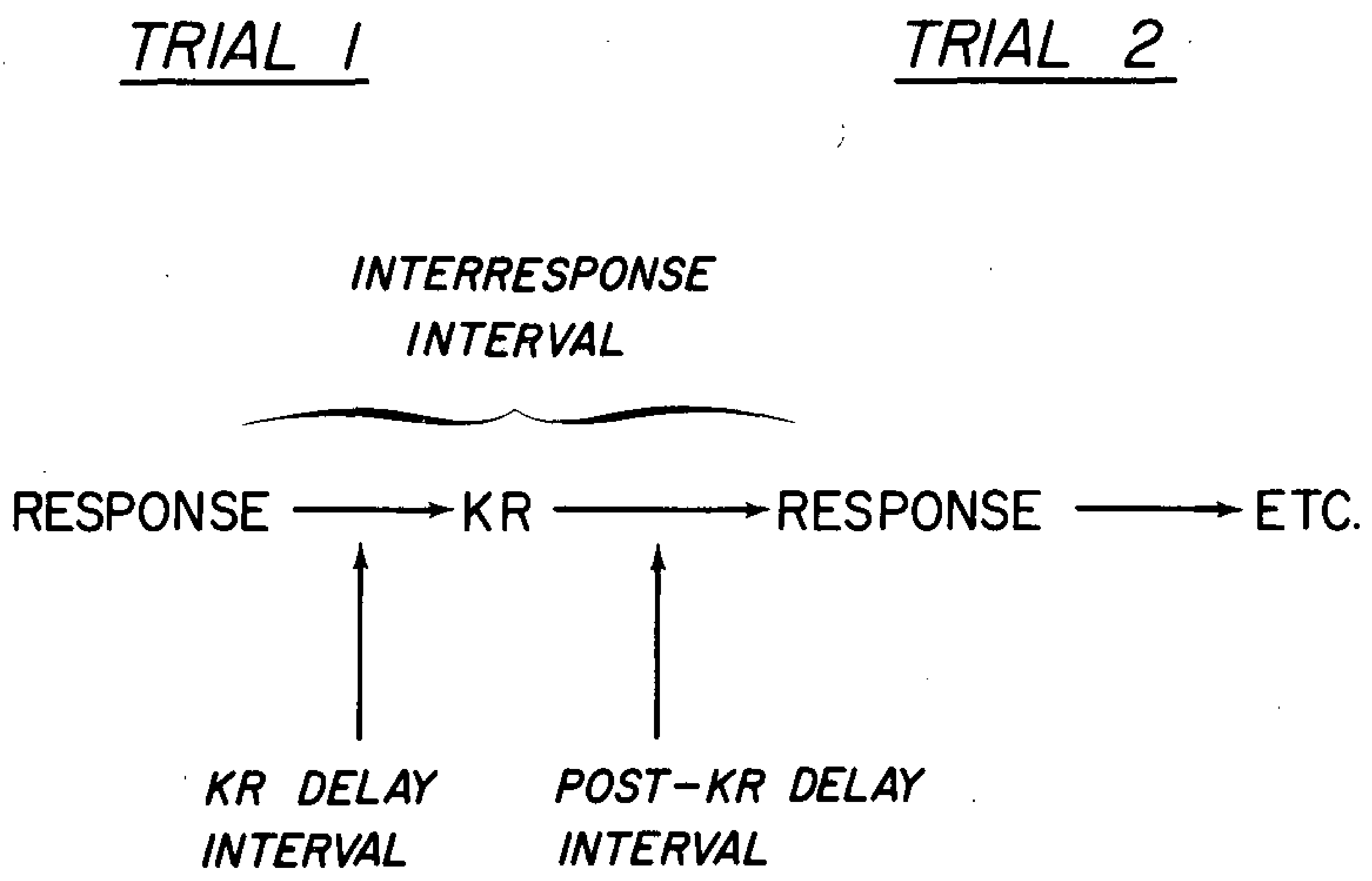

Figure 1. Events and their time relationships in motor learning.

The KR follows a movement, and it can occur after a time delay, called the *KR delay interval.* The time between KR and the next trial can vary also, and it is called the *post-KR delay interval.* The time between the two responses themselves is called the *inter-response interval,* which is the sum of KR-delay and post-KR delay and cannot be defined independently of them.

The first generalization shows a very fundamental principle—KR is a strong determinant of behavior.

> *Performance improvement in acquisition depends on knowledge of results. The rate of improvement depends upon the precision of knowledge of results* (Baker & Young, 1960; Bilodeau, Bilodeau, & Schumsky, 1959; Elwell & Grindley, 1938; Macpherson, Dees, & Grindley, 1948a; Thorndike, 1927; Trowbridge & Cason, 1932).

There were experiments on KR before Thorndike but he was the one who entrenched this principle in psychology. In one of his well-known experiments, Thorndike (1927) used the line drawing task and had blindfolded *S*s draw blocks of 3-, 4-, 5-, or 6-in. lines. In each session there were blocks of 150 lines for each of the four lengths drawn. Qualitative KR was used, and *S* was told "Right" or "Wrong" after each response. For example, the attempt to draw a 3-in. line was "Right" when *S* drew a line that was 3 ± 1/8 in., and "Wrong" otherwise. The median percent correct was 34.5 for the first session, and 54.5 by the seventh session. In a companion study, *S*s drew 5400 lines without KR and there was no change in percent correct from the first to the final session.

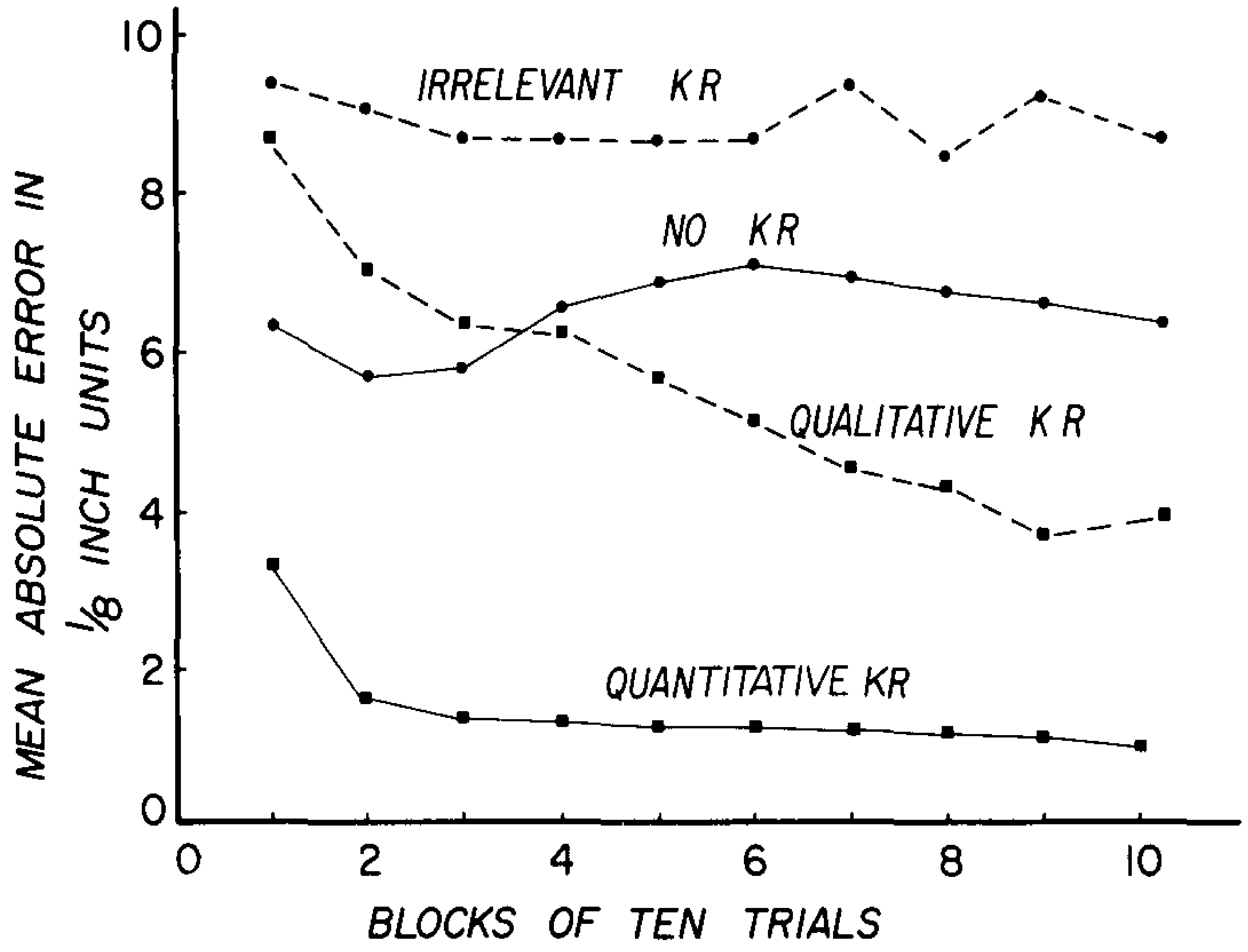

Figure 2. The dependence of performance improvement on KR and its precision. Drawn from tabled values in Trowbridge and Cason (1932).

The next figure illustrates all aspects of this principle, including conformation of the Thorndike data discussed above. The data are from a study by Trowbridge and Cason (1932). A task of drawing 3-in. lines was used. Variables were KR and no-KR, as well as precision of KR. The precision variable was in terms of qualitative vs. quantitative KR. The qualitative KR was "Right" and "Wrong," and quantitative KR was error reported in 1/8-in. units. When *S* made a response that was 1/8 in. too long, *E* would say "Plus 1." If his response was 3/8 in. short, he would say "Minus 3." There was a fourth group that had irrelevant KR, where *E* spoke a nonsense syllable after each response, which was a good control because any response by *E* after each movement might facilitate performance, not just KR. Error was recorded quantitatively regardless of what *S* was told, and both the quantitative and qualitative KR curves showed a steady reduction of error as a function of trials. Notice how much more rapidly the response was acquired with quantitative KR. The no-KR condition remained essentially unchanged over trials, as did the irrelevant KR condition. Why irrelevant KR should produce poorer performance than no-KR is unclear.

Theoretically, the finding that more rapid acquisition results from more precise KR follows from the position that motor learning is a problem to be solved. Information in the form of KR is received and a change in the movement on the next trial is made on the basis of it. When, say, *S* is told "Wrong," he has vague information because he is informed only that an error has been made, but he knows neither the direction nor the amount of error. As a result, the correction will tend to be poor each time and the rate of learning will be slow because the problem is difficult. In contrast, quantitative KR gives the direction and amount of error, and learning is faster.

The next principle affirms that motor learning is under verbal-cognitive control in the first stage of learning. The evidence is indirect because without the goad of theory there has been no reason to be concerned about the verbal control of motor behavior and do experiments on it.

The first stage of acquisition is under verbal-cognitive control.

Elwell and Grindley (1938) reported that *S*s were giving themselves self-instructions like "I must try to do exactly that movement again," and they saw this verbal behavior as mostly occurring in the early stages of learning. Trowbridge and Cason (1932), in the study just discussed, interviewed their *S*s and said that it was clear from *S*s' replies that they verbalized extensively while trying to improve the accuracy of their line-drawing. Trowbridge and Cason (1932, p. 253) concluded that "The motor act of drawing a line was by no means the only psychological activity taking place," which was their way of saying that motor behavior may be less motor than it appears. Bilodeau (1970), using a lever positioning task, instructed *S*s to repeat their last response or change it. She found that *S*s were able to follow these instructions reliably, indicating that the behavior was under *S*'s voluntary control.

Delay of KR is a variable of great practical importance, as well as being in need of theoretical explanation. The precedures of KR delay in human learning are formally equivalent to those for delay on reinforcement in animal learning. The response is made, and sometime later the KR is given. The next principle summarizes the work done on KR delay in motor positioning tasks.

> *Delay of KR has little or no effect on acquisition* (Bilodeau & Bilodeau, 1958b; Bilodeau & Ryan, 1960; Boulter, 1963, 1964; Dyal, 1966; Dyal, Wilson, & Berry, 1965; Lorge & Thorndike, 1935; Saltzman, Kanfer, & Greenspoon, 1955).

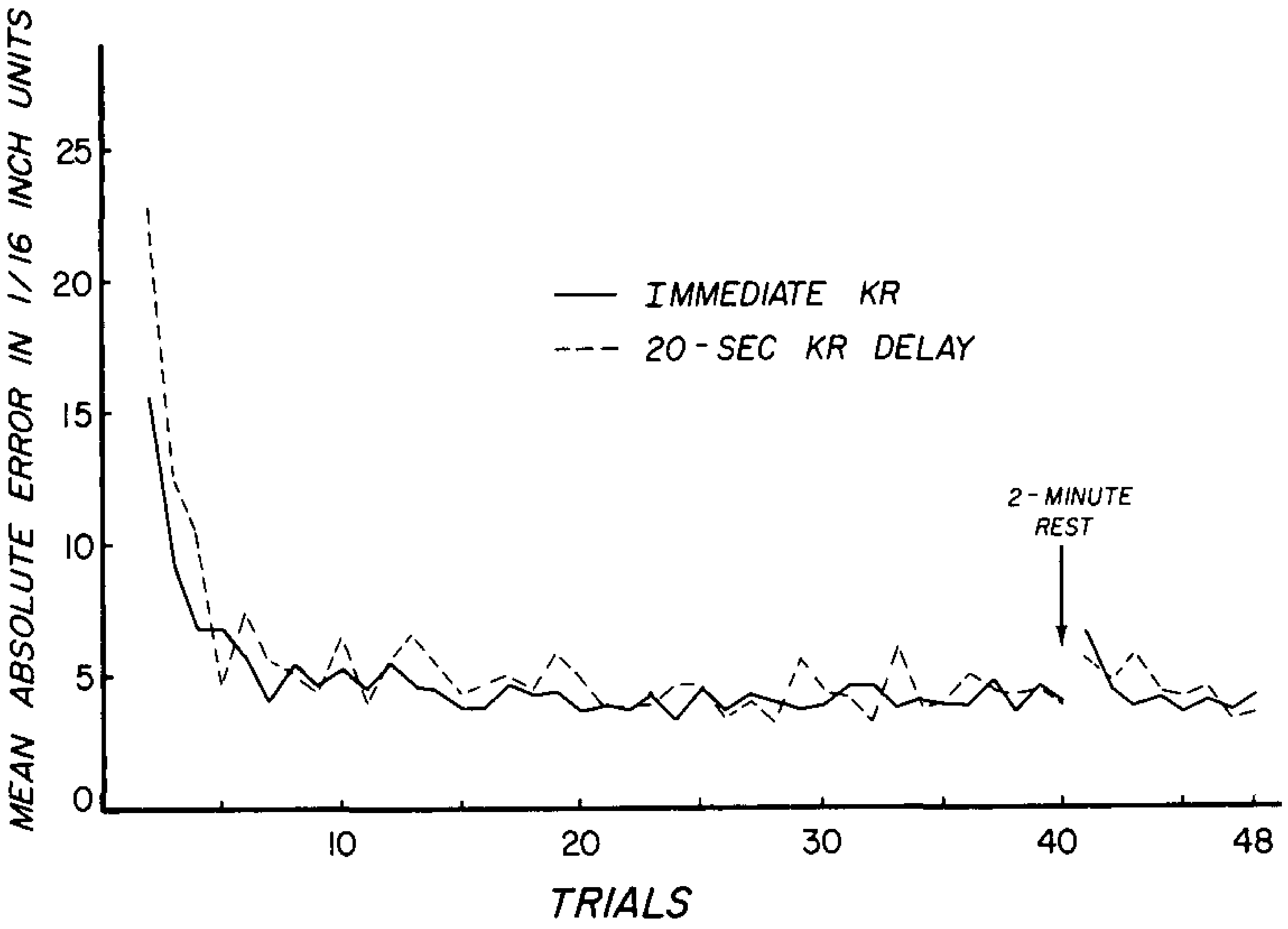

Figure 3. The effect of KR delay on performance in acquisition. From Boulter (1963, 1964).

Fig. 3 has representative data on KR delay by Boulter (1963, 1964), plotted in terms of absolute error. Trial 1 is omitted because the response was prior to the first KR and its delay and was unaffected by it. His *S*s learned a 3-in. movement with quantitative KR in units of 1/16 in. There is more to Boulter's study than shown in the figure, but these two curves are all that is needed for a typical example of KR delay and its effects. The KR delay condition was slightly poorer at the start, but there was little difference on most of the trials. This finding of little or no difference has been found in several experiments and for various KR delay intervals. The first study to show it was Lorge and Thorndike (1935) for a ball-tossing task.

Welford (1968, p. 304) suggested that the method of measurement determines whether or not KR delay will adversely affect acquisition. He based his assertion on a study of Dyal et al. (1965) which found an effect of KR delay when the response was scored correct or not with respect to a scoring zone, and no effect if actual amount of error was used as the measure. It would be nice if the problem could be dismissed this way, but it cannot. Bilodeau and Ryan (1960) examined both percent correct and continuous error measures for their data on KR delay and found the same result for both, which was no effect of KR delay on acquisition. And, a re-working of Boulter's (1963) original data in terms of qualitative "Right" and "Wrong" scoring, with the criterion of correctness being ± 1/4 in. of the required response, gave about the same results as the continuous error measure used in Fig. 3.

Why does KR delay have little or no effect on acquisition? According to the theory, the perceptual trace from feedback stimuli gains an increment of strength when the response is made on a trial, and it can be weakened by forgetting in the interresponse interval. The strength which the perceptual trace has at the start of a trial depends on the interresponse interval; it has nothing to do with the locus of KR. The KR in the Verbal-Motor Stage provides information for the correction required, and the post-KR interval is the place where the information is processed. It is conceivable that the post-KR delay can be so brief that there is insufficient time to process the information and decide upon the correction, or it can be so long that the KR and the correction plan based on it are themselves forgotten. Accepting these restrictions, wide latitude within a given interresponse interval is possible for the length of the KR delay and post-KR delay intervals without affecting performance. The studies on KR delay have ordinarily held the interresponse interval constant and varied the KR delay and post-KR delay intervals within it. Thus, the typical experiment might set an interresponse interval constant at 30 sec. and compare, say, 2 groups. One might have KR delay of 10 sec. and a post-KR delay of 20 sec. The other would have KR delay of 20 sec. and post-KR delay of 10 sec. The expectation, which never materialized for humans, is that the 20-sec. KR delay would produce poorer performance than the 10-sec. delay. According to the theory it would not matter because the interresponse interval was the same for both groups. The Boulter data are an example of this, where the interresponse interval is constant, KR and post-KR delays are manipulated, and the outcome was no performance differences in acquisition.

Denny and his associates (Denny et al., 1960) showed data where interresponse interval was varied and performance conformed to theory. Denny used a line-drawing task and had his *S*s practice until they made 5 consecutive criterion responses of 3 ± 1/4 in. Table 1 has the results, and it also shows the experimental design.

Table 1

Median trials to attain criterion in a line-drawing task.
N = 24/group. The values in parentheses are the interresponse intervals.
From Denny et al. (1960).

		Post-KR Delay (sec.)	
		10	30
KR Delay (sec.)	0	18.5 (10 sec.)	34.5 (30 sec.)
	10	25.5 (20 sec.)	
	20	41.0 (30 sec.)	

Instead of holding the interresponse interval constant as is usually done, Denny allowed it to vary so KR delay, post-KR delay, and interresponse time are all variables in this experiment. Looking down the first column where post-KR delay is constant, trials-to-criterion increased as KR delay increased, which could be taken as evidence that the longer the KR delay the slower the acquisition rate. But notice also that interresponse interval covaries with KR delay, so the effect could just as well be due to interresponse interval. In anticipation of this, Denny included the cell in the upper right-hand corner. Here the interresponse interval was 30 sec., the same as the cell in the lower lefthand corner. The difference between the two conditions is that one has immediate KR and one has delayed KR. The statistical comparison of these two means found no significant difference, indicating that it was interresponse time and not KR delay that affected learning rate. Given this, the increasing values in the first column can be ascribed to increasing interresponse intervals, not increasing KR delay intervals.

Denny was on the right track when he unscrambled KR delay and interresponse time, and designs of this sort can test the general theoretical proposition that with constant interresponse time there can be wide latitude in KR delay and post-KR delay, providing that post-KR delay is long enough to allow information processing. And, whenever interresponse time is increased, the acquisition rate should worsen, regardless of KR delay and post-KR delay. The theoretical explanation is forgetting of the traces over the interresponse interval, and the variables determining forgetting must be kept in mind. Thus, forgetting over the interresponse interval should be less as trials increase because practice increases resistance to forgetting processes.

The post-KR delay is important for the Verbal-Motor Stage because this is the time interval where information processing occurs and *S* decides what to do about KR. Theoretically, the only requirement is that the interval be long enough for information processing to occur. Here is the generalization for post-KR delay.

> *Increasing the post-KR interval up to a point will improve performance level in acquisition* (Bourne & Bunderson, 1963; Bourne et al., 1965; Croll, 1970; Weinberg et al., 1964).

The experiment by Weinberg et al. is the only study on motor learning; the others are on concept or discrimination learning, and they are closely related and give the same results. Weinberg's task was a 10-in. positioning movement, and he used immediate KR with post-KR intervals, of 1, 5, 10, and 20 sec. The results were poorer performance for the 1-sec. interval, but no difference among the other intervals. Weinberg's interpretation, which is the one held here, is that some minimal time is required to process information and, for simple motor tasks, this time period need be no longer than 5 sec. We would expect this time interval to increase as task complexity increases because the cognitive strategy behavior would become more elaborate.

Next is the interpolation of potentially interfering activities in the KR delay and post-KR delay intervals. Interference is one way that we can know about an ongoing process. If a verbal process is hypothesized to occupy an interval, and *S* is forced to engage in verbal activities during the interval and a decrement in his performance is produced, there is evidence that the hypothesis is true.

> *The type of activity in the KR delay or post-KR delay interval does not influence acquisition (KR delay:* Boulter, 1963, 1964. *Post-KR delay:* Blick & Bilodeau, 1963; Larré cited in Bilodeau, 1966, p. 269; McGuigan, 1959; McGuigan et al., 1964).

Boulter (1964) had a 20-sec. KR delay and interpolated similar motor movements, reading consonants, or both, with the hope of finding the type of mechanism that was operating in the KR delay interval. None of these activities had an effect on performance in acquisition. This is disconcerting for the theory which holds that the perceptual trace is operating in the interval. The interpolation of similar motor movements would be expected to degrade acquisition but it did not. Perhaps a weakened or distorted perceptual trace is sufficient for correction of the movement on the next trial, although at some point the trace must become poor enough to impair performance.

Studies of interpolated activity in the post-KR interval are easier to explain because the interpolation has always been motor responses. With the theoretical assumption that the post-KR interval is a period of verbal-cognitive behavior, it is not surprising that motor activities fail to interfere. A proper choice of verbal-cognitive responses should be able to show an effect, but without theory there has been no cause so far to interpolate verbal activities.

KR Withdrawal

It is common to refer to the withdrawal of KR as "extinction." There is a correctness about this usage of extinction for a particular theoretical frame of reference. It is reasonable to see KR withdrawal as extinction if KR is seen as reinforcement, but this is an inappropriate connotation for the informational view of KR because reinforcement implies a strengthening and extinction implies a weakening of the associative connection. The informational view of KR does not imply weakening of the response when KR is withdrawn. Another reason the term extinction is inappropriate is that it carries the connotation of performance deterioration. As will be discussed, human performance does not always deteriorate when KR is withdrawn.

The Verbal-Motor Stage will be under discussion first, where the number of KR trials given before KR withdrawal is relatively small. The first generalization for KR withdrawal in the Verbal-Motor Stage is well established.

> *Withdrawal of KR produces deterioration of performance when level of training is low or moderate* (Bilodeau, Bilodeau, & Schumsky, 1959; Boulter, 1963, 1964; Elwell & Grindley, 1938; Macpherson, Dees, & Grindley, 1948a, 1948b; Schumsky, Grasha, & Seymann, 1966).

Representative data from Bilodeau, Bilodeau, and Schumsky (1959) are shown in Fig. 4. They used a lever positioning task, where *S* reached through an opening in a panel and positioned a hidden lever. The correct response was a 33-deg. displacement of the lever. The top curve is no-KR throughout, and no learning is shown, as expected. The bottom curve is KR on every trial, and the standard learning curve develops, as expected. The other two curves represent KR withdrawal. The second curve shows 2 KR trials followed by 18 trials without KR. The third curve had KR withdrawn after 6 trials. The performance deterioration is regular in both cases.

The next principle has the effects of KR withdrawal when KR has been delayed in acquisition and *S* has had no intentionally interpolated activity in the delay.

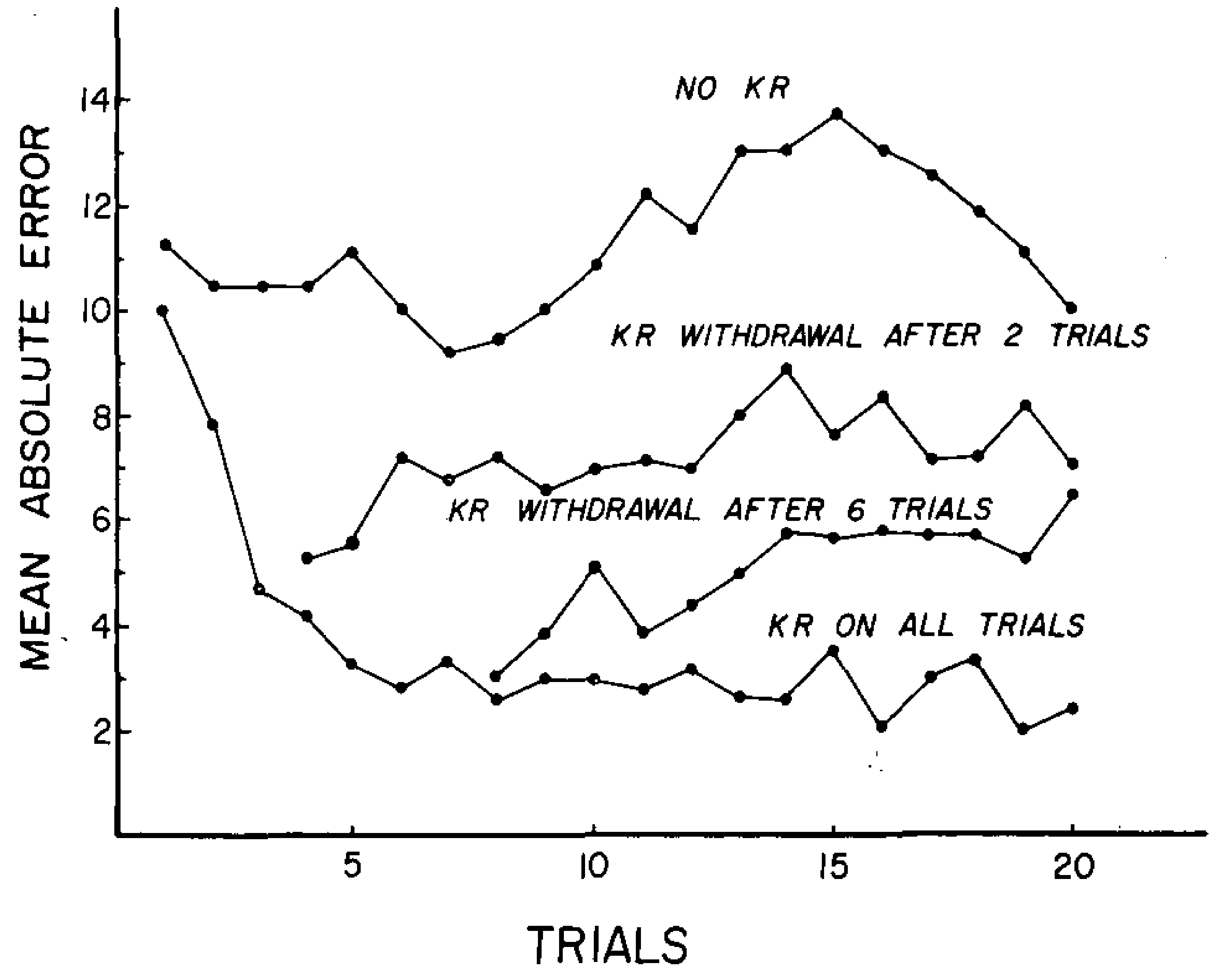

Figure 4. The effect of KR withdrawal on motor performance. From Bilodeau, Bilodeau, and Schumsky (1959).

> *When KR is delayed in acquisition, and S rests during the delay interval, the effect on performance when KR is withdrawn is no different than when immediate KR is used* (Boulter, 1963, 1964; Dyal, Wilson, & Berry, 1965).

The next generalization shows that the preceding point holds only when *S* rests during the KR delay interval.

> *When KR is delayed in acquisition, and S engages in deliberate verbal or motor activity during the delay interval, the effect of KR withdrawal is poorer performance than when S rests.*

Boulter (1963, 1964), whose acquisition data were discussed before, has data illustrating the last two principles. Fig. 5 shows performance on 20 KR withdrawal trials, which was a common treatment for all groups following 48 acquisition trials where each group received a different treatment, which is described on the graph. The two lower curves represent performance KR withdrawal after immediate KR and 20-sec. KR delay where *S* rested during the delay interval, and there was no significant difference between the curves. However, the top three curves had acquisition with activities interpolated in the KR delay interval, and performances were much poorer. The interpolated verbal activity was in the form

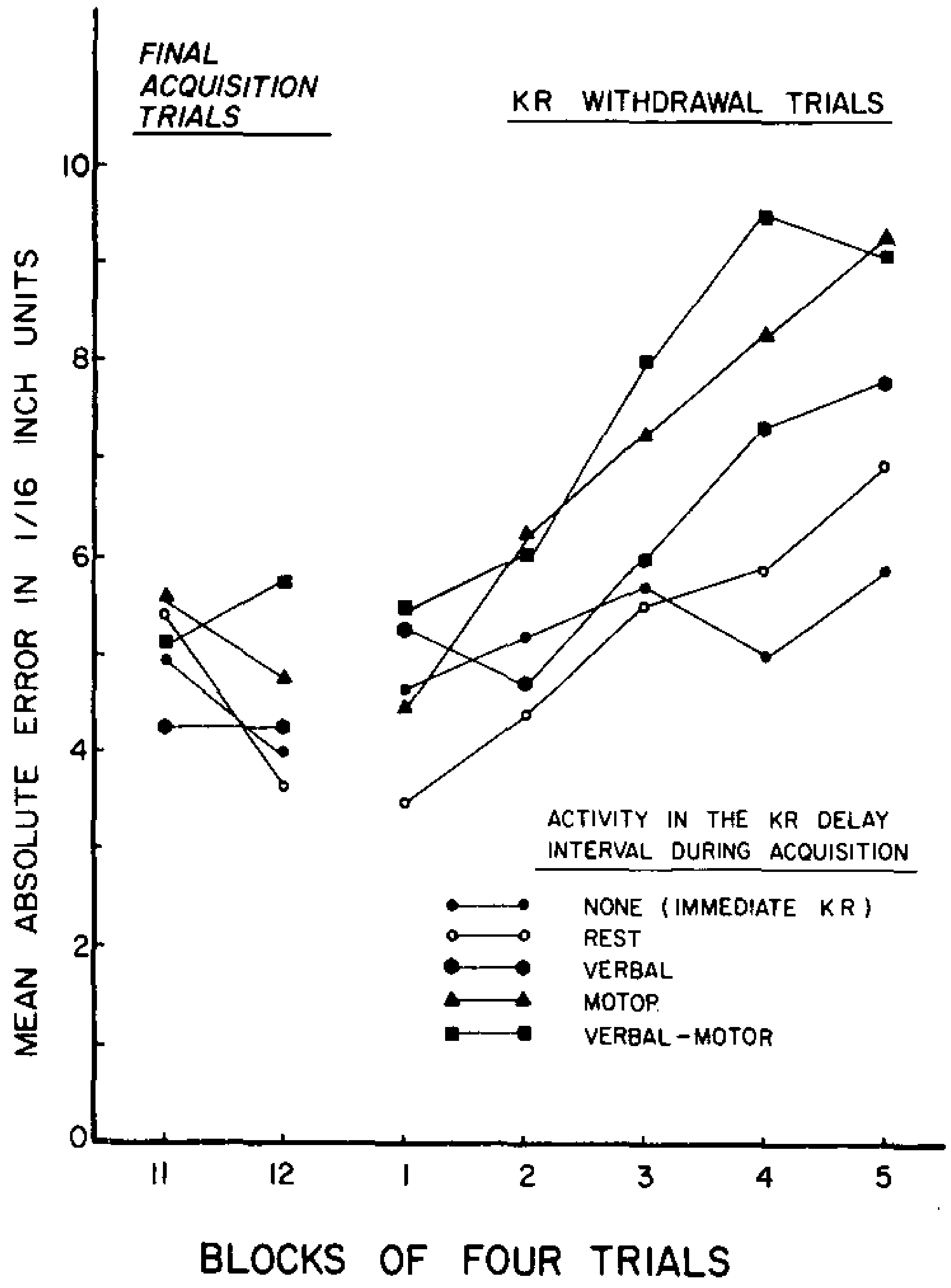

Figure 5. The effect of KR withdrawal on motor performance as a function of activities interpolated in the KR delay interval during acquisition. From Boulter (1963, 1964).

of reading random consonants, the making of similar movements, or both. Verbal activity worsened performance, but the motor and the combined verbal-motor activities gave the poorest performance of all.

The next principle shows that intentional activity in the post-KR delay interval during acquisition also has a damaging effect on performance when KR is withdrawn.

Activity in the post-KR delay interval during acquisition worsens performance when KR is withdrawn.

This generalization is based on experiments by McGuigan (1959) and McGuigan et al. (1964) who showed that even a simple movement of the hand during the post-KR delay interval can lower performance when KR was withdrawn. The post-KR delay interval has not been studied as extensively as KR delay, but the results of these two experiments are consistent and are a sufficient basis for a generalization.

How can theory account for these findings in the Verbal-Motor Stage? There are 3 ideas from the theory that are needed. First, responses are seldom repeated in the Verbal-Motor Stage, which is an early stage of training, and so each of their perceptual traces will be weak. Second, the perceptual traces will be weakened by forgetting processes, and it would be particularly so with weak traces. Typically, this would be short-term retention for the kind of experimental paradigm under discussion here, and the evidence for short-term motor forgetting is now considerable (Adams, 1967, 1969b; Adams & Dijkstra, 1966; Ascoli & Schmidt, 1969; Schmidt & Ascoli, 1970; Stelmach, 1969a, 1969b; Williams, 1971). Third, KR withdrawal should not be seen as a nonlearning test condition where the effects of prior learning are evaluated. Rather, KR withdrawal is simply a *change* in the learning conditions. Past learning has its influence but learning still continues when the task conditions are changed. The perceptual trace is laid down by response-produced stimuli each time a movement occurs, and the movements made when KR is withdrawn lay down their perceptual traces in the same fashion as when KR is present.

Given these three theoretical ingredients, why does performance deteriorate in the Verbal-Motor Stage when KR is withdrawn? When KR is withdrawn, the first withdrawal trial is like another acquisition trial because the KR from the last trial is available for adjusting the response, and it would be in the trend of preceding responses. But, from then on, in the immediate trials that follow, KR is no longer available, and each response is on the basis of perceptual traces alone which are weak perceptual traces from acquisition, are undergoing forgetting, and are becoming increasingly poor guides for response. The perceptual traces from the final KR trials representing the best performance are the most recent and strongest traces, and they dominate the early trials of KR. But, as they are gradually forgotten, performance deteriorates. This is only the beginning of the story, however. The theory assumes that a perceptual trace is imprinted each time a movement is made, so the responses made during KR withdrawal themselves are learned. These are "wrong" responses, of course, based as they are on the perceptual traces of earlier learning that have been weakened by forgetting, and so performance worsens. Thus, the traces from responses on the terminal acquisition trials start the trend of response deterioration because of their forgetting, and these deteriorated responses themselves come to provide perceptual traces that are the basis of further deterioration because of new and inappropriate learning. The trend does not appear to go on indefinitely, with error getting absurdly large, probably because the new perceptual traces come to define a new level at which performance stabilizes.

What about an explanation for the phenomena associated with KR delay and post-KR delay? That immediate KR and KR delay with an empty rest interval produce the same performance when KR is withdrawn is understandable. Both of these conditions have the same performance in acquisition over the same time span (as these experiments are customarily run), so they should have the same perceptual traces in the KR withdrawal trials and produce the same performance.

Interfering activities in the KR delay and post-KR delay intervals during acquisition degrade performance when KR is withdrawn, and theoretically these activities are seen as weakening the perceptual trace, with poorer performance resulting from greater interference. Interfering activities in the KR delay, however, had no affect on acquisition performance (Boulter, 1963, 1964). With the interference and the time intervals in acquisition that Boulter used, the weakening of the trace would appear to be insufficient for degrading the acquisition performance. Longer interresponse intervals or stronger interference conditions ought to show an effect of interpolated activity in acquisition. If the theory is correct it should be possible to devise conditions of interference that would worsen performance both in acquisition and KR withdrawal trials.

Next, consider KR withdrawal in the Motor Stage where the response is fully learned after a comparatively large number of trials. This is a very interesting stage because, as the following principle says, self-learning can occur when KR is withdrawn.

After a relatively large amount of training, learning can continue when KR is withdrawn.

This has been called the subjective reinforcement effect which, as the name implies, is learning in the absence of KR and on the basis of internal information. There are various lines of evidence for this phenomenon in verbal learning (Adams, 1967, pp. 295-302; Adams & Brav, 1970, p. 392), but only one study in motor learning hints of it. Despite the lack of strong evidence from motor learning, the aggregate evidence from verbal and motor learning is sufficient to justify the principle.

The motor data are from Bilodeau and Bilodeau (1958a), and they are instructive because they show the effects of KR withdrawal for both early and late in learning, which are the Verbal-Motor and Motor Stages of the theory. Their frame of reference was partial reinforcement, and a lever positioning task was used. The KR was administered on every 10th trial, so responses between every 10th one are instances of KR withdrawal. Straight lines have been drawn through the responses without KR to better show their trends. Early in learning the trials without KR show a trend towards increasing error in each block of 10, which is

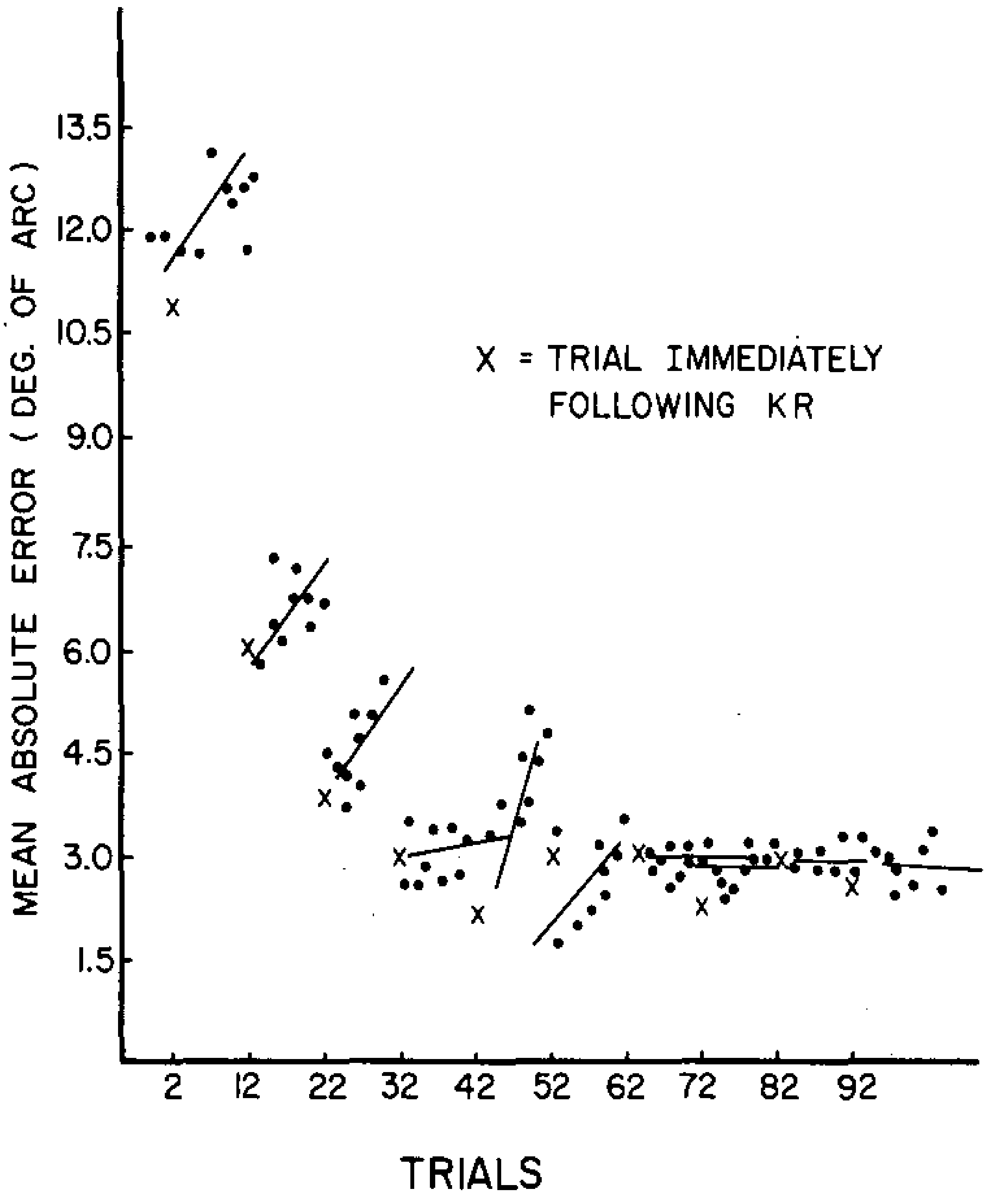

Figure 6. The effect of KR withdrawal after various degrees of learning. From Bilodeau and Bilodeau (1958a).

the performance deterioration in the Verbal-Motor Stage. However, notice the trend over blocks of trials. The no-KR trials steadily show less and less deterioration until, at the end of training, the no-KR responses are showing the same general trend as the responses with KR. As a minimum, performance is sustained in the absence of KR and perhaps performance increments accrue.

The theoretical explanation of performance in the KR withdrawal trials has the same ingredients for the Motor Stage as the Verbal-Motor Stage. *S*s in the Verbal-Motor Stage hardly ever made the same response movement each time, but here *S* is regularly making the same response each time. His performance is very good, and the perceptual trace for the correct response is strong because *S* has repeated the correct response many times. Moreover, the correct response tends to remain strong because it has been repeated enough times to make it relatively resistant to forgetting. In the early trials of KR withdrawal *S* keeps repeating the correct response because he is basing it on the strong perceptual trace existing in the final acquisition trials, and each time he makes this correct response the perceptual trace receives added strength from the response-produced stimuli and grows stronger. The result is more learning, and all without KR.

Pivotal Issues and Future Directions

The theory has some gratifying merit in accommodating empirical data, and it obviously has other implications that are amenable to empirical test. Rather than detailing some of these implications, this section will examine topics on which the significant refinement of closed-loop theory may very well depend. There is little data on any of them; they represent research programs for the future.

First, the most problematic part of the theory is the assumption of two traces rather than one. It would have been easy to assume that an image or perceptual trace built from the feedback stimuli from movement is the single controlling state, and there would have been justification for this assumption in the literature (Greenwald, 1970; James, 1890b, Chapter 26). Three reasons were given for assuming the memory trace as a second state, 2 based on internal consistency requirements of the theory and the other on empirical data from verbal learning showing that recall and recognition depend on different states, which is the strongest reason. Recall and recognition are separate measures in verbal learning and their comparison is easy, but to say that recall and recognition are based on 2 different states and both occur in a unified motor act is an hypothesis which is conceptually the same but far more difficult to demonstrate. One experimental approach to show the separate existence of the memory trace and the perceptual trace would be to demonstrate that the choice of a motor direction is independent of the length of the movement. Presumably, learning of the movement's direction could occur with movement length randomized. Another approach, which is under study in our laboratory[4], would be to show that feedback stimuli affect the learning of movement extent but not movement choice. If these ideas produce positive results they support the position of 2 traces with the memory trace a limited program, but if the results are negative there is the new problem of the extensiveness of the memory trace. How long a response sequence does it determine? As a limit, there could be a full memory trace to run off the response and a parallel perceptual trace to check it. This possibility seems reasonable when the rubric of self-paced tasks is abandoned and rapid, paced tasks are considered. When ballistic tasks are considered the movement is run off without the opportunity for correction, as if a motor program is driving it, with the appraisal of correctness coming afterwards. One of Lashley's anecdotal justifications for a motor program was the high-speed fingers of a musician (Lashley, 1951, p. 123). This example has been visible for 20 yr. as proof of a motor program concept

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[4] *Ernest T. Goetz, investigator.*

and it has been curiously resistant to experimental test for as long. Empirical test should not be difficult, however. While Lashley did not concern himself with learning and the motor program, we might surmise that the acquisition of high-speed performance should be unaffected by the characteristics of feedback stimuli in the task. If it is protested that this is an unfair test because a motor program might be the gradually acquired freedom from feedback stimuli, then highly trained *S*s who have practiced with unimpaired feedback should not suffer when their feedback stimuli are attenuated. With all the evidence that feedback stimuli affect performance, and with the studies of Fleishman and Hempel (1954) and Fleishman and Rich (1963) on the increasing importance of proprioception as practice progresses, it seems doubtful that a concert pianist's swift cadenza would go uninfluenced by the withdrawal of, say, his proprioceptive feedback.

Second, this closed-loop theory, as well as others in non-learning fields, rely on peripheral feedback for error detection, where error detection is the comparison of feedback against a reference for the correct response. As intuitively obvious as this is to theorists, feedback is unproved as a key element in error detection. Feedback is unquestionably a determiner of human performance (Adams, 1968; Adams et al., 1969; Chase et al., 1961; Laszlo, 1966, 1967a, 1967b, 1968; Laszlo & Manning, 1970; Laszlo, Shamoon, & Sanson-Fisher, 1969; Yates, 1963), but it has not been shown that feedback is necessary in the detection of errors, and this is a fundamental consideration for closed-loop theory which pivots strongly on mechanisms of error processing. Closed-loop description is not rejected if peripheral feedback does not govern error processing. Konorski (1962) and Teuber (1964) have discussed "corollary discharge," where sensory fibers which link the motor and sensory areas of the brain are presumably aroused when a movement is initiated, and it is these which may be compared against a central reference mechanism for the error test. If so, error processing would be central. Peripheral feedback under these revised circumstances would have to be viewed anew, perhaps as a performance variable inducing a general arousal or tonic effect, as Wilson has inferred from his insect studies.

Third, how is an error corrected? Error detection is straightforward enough in the theory, where feedback is compared against the reference for the correct response, but what determines the particular response that is given in correction? Within closed-loop theory, error correction is a matter of selecting a new memory trace that will produce a response to match the perceptual trace, and this difficult problem remains untouched. Greenwald (1970) has attempted an explanation of error correction. He used the principle of response chaining, where the correct response follows an error by becoming conditioned to the response-produced stimuli from the wrong response. Each possible error becomes conditioned to the correct response, and so the correction of errors becomes increasingly efficient as learning progresses. This explanation could be disproved by showing that errors which have never occurred before can be detected and corrected, and this would probably be easy to demonstrate.

Fourth, and last, there is the general feeling in the literature, and nothing to contradict it in the theory presented here, that all feedback channels operate over all practice trials and the more channels the better. From the research of Laszlo and others where feedback channels have been manipulated, there is no doubt that generous and multiple sources of feedback benefit performance. But this generalization may need revision because anecdotal evidence suggests that some channels increase their potency and others lose theirs as performance becomes very skilled. Experienced typists and musicians who perform by touch say that their proficiency declines sharply when they watch their fingers. The visual channel, which undoubtedly was used in the beginning, becomes impairing after large amounts of practice. Using factor analytic techniques Fleishman and Hempel (1954) and Fleishman and Rich (1963) demonstrated increased dependence on proprioception as motor practice progressed.

The operational detailing of questions such as these will not be easy. Nevertheless the questions must be asked in the hopes of arriving at a refined closed-loop theory, or perhaps some other theory, that will place us ahead of Thorndike's theory that has dominated motor learning in this century. The S-R theory that comes to us from Thorndike has been far from a poor state of affairs because many useful scientific regularities have been collected under its flag. However, if the various mechanisms which have been discussed under closed-loop theory somehow work to determine learning and performance, then laws collected under an open-loop framework are destined to have a low ceiling on their scientific power because too many fundamental variables will have been left out.

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