

Learning of Movement Sequences

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The instrumental learning of the behavioral act, defined as a response class whose members are in temporal contiguity with reinforcement, has slowed our understanding of how movement sequences are learned. This is because the act does not require consideration of the movement patterns of the responses that produce the reinforcement. Notwithstanding, throughout learning's experimental history psychologists have asked where movement segments come from and how they are organized into more complex movement sequences. From the beginning, animal psychologists have asked the extent to which movement segments and their organization into sequences is instinctive. The answers have ranged from a minimum influence of instinct, where learning provides the organization to the ethological view, which deemphasizes learning and stresses instinct as the organizer. For decades the response chaining hypothesis has been the explanation of how segments are organized by learning; however, modern research does not support it and has tilted the explanation toward a cognitive interpretation. A parallel account of how humans learn movement sequences is also presented. The positions of Piaget (1952) and Bruner (e.g., 1973) from developmental psychology, as well as those of Lashley (1951) and more recent analysts of movement regulation, are reviewed. Here, too, cognitive interpretations are prevailing. A concluding discussion finds that the often-asked question "What is learned?" still pertains to motor learning, and that the act, useful though it has been, does not deserve status as the response unit of the laws of instrumental learning. It is suggested that animal and human motor behavior settle on error as the focus of measurement.

What is the origin of movement segments, and how are they organized into longer, integrated movement sequences? Long serial sequences abound in the behavior that learning psychologists study, from running mazes to industrial skills. The topic has never been mainstream because preoccupation with the act in the psychology of learning effectively defined the issue away and placed it outside the bounds of meaningful scientific questions to ask, as I review in the first section. For some, an interest in serial action did not begin until Lashley (1951). Lashley drew most of his examples from language and explained them in a way that was attractive to the advocates of cognitive psychology. The topic existed long before Lashley's analysis, however, and this article examines the earlier background as well as Lashley and recent stances.

The emphasis of this article is the instru-

mental learning of animal and human motor behavior. For terminological consistency, a comparatively long serial movement pattern is called a *movement sequence*, and its parts are called *movement segments*.

The Act as the Unit of Response

Despairing of structuralist psychology that sought laws by the introspection of consciousness, Watson (1913) asserted his behaviorism, which had the laws of psychology drawn from the correlations between objective stimuli and responses to them. This axiom about stimuli and responses became increasingly reasonable to psychology as behaviorism gained ground, but it was not without its methodological problems. Though one may be successful in an objective definition of a stimulus, its influence on behavior is assignable to the part that falls on the receptors and is perceptually processed. Being behavior-dependent, there is no way to guarantee an objective definition of a stimulus. The response has similar uncertain-

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ties. Response variability is a fact of life for psychology.

How can the objective laws of psychology be specified if its independent and dependent variables cannot be reliably defined? Skinner (1935) faced this issue. He concluded that the solution was to treat stimulus and response as class terms and express the laws of psychology as relations between classes. A class can contain an indefinitely large number of different elements, but it is definable nevertheless. The bar-pressing response in the Skinner box is sufficiently defined as bar pressing whether it is with the right or left paw; the responses are of the class bar pressing and are "quantitatively mutually replaceable" (Skinner, 1935, p. 45). A means of defining the response class was discussed but not solved in the 1935 article, but Skinner had a solution: "In the case of conditioned operant behavior the defining property of a class is exactly that given by the conditions of reinforcement" (Skinner, 1938, p. 38). Any response that produces the reinforcement is a member of the class. In other words, differences in movement pattern do not matter as long as they are successful in gaining the reinforcement; it is the temporal contiguity of response and reinforcer that matters (Hawkes & Shimp, 1975; Honig & Staddon, 1977, p. 2; Shimp, 1975, 1976). Guthrie (1952, pp. 27-28) was the holdout among theorists by contending that movement patterns were learned in response to a stimulus. Guthrie and Horton (1946) found that the reinforced movements of their feline subjects were stereotyped. This finding was seen as evidence that movement patterns were learned and that movement patterns, not acts, deserved to be the basic dependent variable for instrumental learning. Guthrie's contention never caught on.

Investigators of human motor learning could be thought of as having had a special interest in the learning of movement sequences, and not being swept along with the psychology of the act, but not so. They were strongly influenced by the Thorndike (1911, 1927) tradition, which involved the instrumental learning of response acts, and they studied the response act like everyone else (Adams, 1978). Consider a motor task of drawing a 3-in line, which was a research task

that Thorndike (1927) used in his learning studies. The blindfolded subject was told "right" or "wrong" after each response. The act of successfully drawing the line elicited reinforcement ("right") regardless of whether the movement pattern was fast or slow, choppy or smooth.

The emphasis on response acts did not teach much about the learning of movement sequences, but the approach had an impressive record of success nevertheless because it yielded reliable data and laws. There is no question that the act is methodologically legitimate. However, preoccupation with the act has not entirely steered psychologists from asking questions about where movement segments come from and how they are organized into movement sequences. The topic has been with us since the beginning of learning's experimental history.

Where Do Movement Segments Come From and How Much Organization Do They Have?

The question is related to instinct. Organisms are capable of movement at birth or after some maturation. How much organization of movement do infants have, and how does it affect the learning of movement sequences? The research theme of biological constraints on learning in modern comparative psychology (e.g., Hinde & Stevenson-Hinde, 1973; Shettleworth, 1975) is biologically endowed behavioral organization. Finding it hard to teach an animal a response that runs against its native tendencies, modern investigators have evidence that genetically hard-wired behavioral patterns constrain what can be learned. The amount of instinctive organization for different species and its relation to the learning of movement sequences depends on the historical time and the scientific discipline. Early comparative psychologists asserted minimal instinctive influences and maximal learning influences on organization, whereas ethologists, in the biological tradition, saw fully organized instinctive movement patterns that evolved to serve an organism's adaptation to its environment. Ethologists gave learning a lesser role. Modern comparative psychology has arrived at a synthesis of these two views.

Early Comparative Psychologists Believed in Minimal Instinctive Motor Organization

A point of view that antedates behaviorism but is sustained by it is this: An organism has an instinctive and spontaneous tendency to make a large number of random movements, and it is learning that connects them into an organized movement sequence. I call this the random movements hypothesis.

Insofar as I have been able to discover, Alexander Bain (1868, 1888) was the originator of the view that there is a pool of spontaneous movements that is the substrate of all motor learning. (Bain was a British associationist philosopher who was influential in the latter half of the 19th century.) Bain was thinking primarily of movement that occurred in the absence of exteroceptive stimulation of the senses when he wrote about spontaneous activity (1868, p. 64), not instinct. It does not follow that spontaneous movements would be random, although Bain (1968, pp. 303–305) occasionally referred to them in that way. The comparative psychologists at the end of the 19th century and the beginning of the 20th century appeared to adopt Bain's position and make it a systematic part of the psychology of learning for both lower animals and humans, giving it the special twist that the source of random movements is instinctive. I hasten to add that the link between Bain and comparative psychology is inferential. Early comparative psychologists did not concern themselves with Bain, although they were a generation who undoubtedly read him and could have been influenced by him.

Morgan (1896) was an early and influential comparative psychologist, and he advocated the random movements hypothesis as did other investigators (Dashiell, 1928; Hull, 1943, p. 25; Kantor, 1921; Kuo, 1921; Skinner, 1953, pp. 92–93, 1966; Watson, 1914, 1919). Morgan (1896) spoke for them all:

Just as a sculptor carves a statue out of a block of marble, so does acquisition carve an activity out of a mass of given random movements. Or just as an architect builds a cathedral out of an indefinite mass of material by selecting, shaping, and bringing into relation the given parts, so does acquisition build an habitual response out of a given number of indefinite movements by selecting, modifying, and bringing them into relation. It is the definite, coordinated, response activity that is acquired. (p. 23)

Kuo (1921), a behaviorist and best remembered for his strong antiinstinct views, echoed Morgan's (1896) architectural metaphor when he discussed the nest-building instinct in birds:

The mechanisms and the subordinated or constituent activities [random movements] which are combined to produce a complete reaction of nest building are practically the same as those that they have employed in eating, mating, fighting, flight, etc." (Kuo, 1921, p. 652)

Watson (1919, chap. 9) made the most extravagant use of the random movements hypothesis in his explanation of language learning and thought, a theory which is still mentioned, though never praised, in textbooks. According to Watson, instinctive random movements of the sound-producing vocal cords are shaped into word and sentence sequences through learning, just as any movement sequence is learned. Thoughts are covert vocal-habit sequences, which are "not different in essence from tennis-playing, swimming, or any other overt activity" (Watson, 1919, p. 325).

Tolman (1920, 1922) revealed himself early as a behaviorist with a cognitive flair. He believed movement segments are assembled into a movement sequence, but he did not believe that they were random. Rather, they were chosen by a "determining adjustment" (Tolman, 1920) or a "driving adjustment" (Tolman, 1922), which are motives that select movements purposefully. A movement sequence by which an animal learns to alleviate its hunger is not assembled from a set of random movements but from a set of quasi-organized instinctive food-seeking responses. Moreover, there can be different sets of these goal-seeking responses because the animal can attain a goal in different ways. The goal dominates the selection of the movement sequence; the movement sequence is a means to the end. McDougall (1921) was prominently associated with this purposive view also, but not with the psychology of learning as Tolman was.

Schiller (1952) did not emphasize randomness, but he accepted the view that movement sequences are assembled from innate movement segments, and he was the only one who asked what these original movements were like in animals. Furthermore, Schiller asked if the organization of movement segments into sequences was not fundamentally a matter of

perceptual, rather than motor, organization. His observations were made on monkeys and chimpanzees of progressive ages in problem-solving situations. He concluded against perceptual organization and for motor organization, and for the maturation of innate motor patterns. There was an age gradient in problem solving, with older animals solving problems faster and with problem-solving capability directly related to amount and variety of motor responses that were observed in play. He favored his maturational explanation of increased complexity of movement segments with age.

Ethologists Believe in Extensive Instinctive Motor Organization

A major place for learning and a minor place for instinct was an axiom of early comparative psychology. In the nature-nurture controversy, early comparative psychology espoused learning. It is easy to see behaviorism as causal for this point of view, because it was indifferent to the role of instincts for behavior and awed with the role of learning. The random movements hypothesis is an example. The movement segments which an organism emitted randomly were biologically given, but that was trivial compared with learning and how it was responsible for the marvelously varied movement sequences of the animal world.¹

This is not true of ethology (e.g., Lorenz, 1970, 1971, 1981; Tinbergen, 1951). Originating in biology and steeped in the theory of biological evolution, ethologists, observing animals in their natural settings, saw a rich array of movement patterns that appeared without apparent learning, and so movement patterns must have instincts as their origins. Lorenz, a founder of ethology, acknowledged the contributions of behaviorists to learning (Lorenz, 1981, p. 70). Nevertheless, he criticized behaviorism for its excessive concentration on learning, for its artificial experimental situations, and for ignoring instinctive behavior.

For Lorenz (1970, 1971, 1981), biological evolutionary processes direct behavior just as they direct skeletal structure and organs. Behavior is as much a factor for adaptation and survival as the strength of limbs or the sharpness of eyes. The instinctive movement pattern, fixed motor pattern, or fixed action pattern,

as it has been called, is basic for Lorenz. A species is capable of movement patterns that are inherited and can range from simple movement segments to complex sequences like nest building, mating, or fighting. These fixed action patterns are distinctive for a species. Particular configurations of stimuli will release the fixed action patterns by activation of the innate releasing mechanism. Despite the emphasis on instinct, Lorenz did not ignore learning. Learning is the way that an organism adapts to an uncertain environment. Some of the observed variability in movement sequences is due to the fact that fixed action patterns can be mixed with learned patterns, which he called instinct-conditioning intercalation (Lorenz, 1970, p. 269). There is also variability with respect to stimulus configurations that elicit fixed action patterns, and imprinting is the perceptual learning mechanism that is responsible. The innate releasing mechanism is bound by the configuration of a particular class of stimuli, but imprinting is acquired recognition that gives an organism the potential to respond to a much wider range of stimuli. Following a moving object is a fixed action pattern for a duckling; through imprinting the duckling can learn to follow its mother or a human.

It is worth noting that Lorenz's (1970) mode of thinking was similar to the random movements hypothesis. Lorenz wrote of simple instinctive motor patterns, like various kinds of locomotion, grasping, and pecking that operate like tools, or organs which the animal can use for a variety of purposes (Lorenz, 1970, pp. 294-295). Thus, a bird's pecking response, which instinct has made an invariant, can be used for eating, fighting, and nest building. Learning can be one of the ways that these basic units are organized into longer sequences. The same is true for shaping, where reinforce-

¹ Timberlake (in press) pointed out that several early comparative psychologists, including Watson, flirted with an ethological position that gave a larger role to instincts, but they never did anything with it. One can only speculate why. One possible reason is disenchantment with the facile use that James (1890) and McDougall (1921) made of instincts. Another is the apparent power of the random movements hypothesis. It can explain all movement sequences, and there is no need to identify instinctive movement sequences, to distinguish them from learned sequences, and to show how the two interact.

ment is used to train a long movement sequence. The parts that comprise the sequence are instinctive units, usually movements (Lorenz, 1981, pp. 316, 320). Timberlake (in press) had a similar view. Operating from a comparative psychology stance and impressed with the importance of ethological findings for the psychology of learning, Timberlake indicated that the behavior of animals was organized into major systems (e.g., feeding and mating) which are composed of organizations of behavioral modules that are in turn made up of perceptual-motor response patterns. Thus, a feeding system would include modules of investigation, food handling, hoarding, and ingestion, and each module would be a characteristic pattern of movements. Systems and their modules and responses have a loose hierarchical structure that can be modified by learning as the organism adjusts to an inconsistent environment. Entire systems may be elicited or inhibited as the result of learning.

Research on electrical stimulation of the brainstem of animals underscores the strong role that ethologists give instinct. Hypothalamic stimulation can reliably arouse species-specific behavior patterns that are characteristic of the instinctive behavior associated with feeding, drinking, fighting, mating, and so on (e.g., Bullock, 1965; Delgado, 1965; Glickman, 1973; Glickman & Schiff, 1967; Valenstein, Cox, & Kakolewski, 1970; von Holst & von Saint Paul, 1973). These behavioral patterns, which are hypothesized to be preformed in the brain, are a function of the parameters of electrical stimulation (von Holst & von Saint Paul, 1973), the environmental situation (Bullock, 1965; Valenstein, Cox, & Kakolewski, 1970; von Holst & von Saint Paul, 1973), and experience (Eibl-Eibesfeldt, 1975). Von Holst and von Saint Paul (1973) elicited complete complex sequences in the chicken, like fleeing or defensive behavior, but they also found that elements of these complex sequences could be elicited in isolation. Electrical stimulation can cause the chicken to repeat the snapping and swallowing segment from the entire hunger sequence. Furthermore, the same elements were found in different sequences. Pecking on the ground is an element of hunger behavior or fighting behavior. Sitting is a part of sleeping or brooding. Von Holst and von Saint Paul emphasized the synthesizing capabilities of the

central nervous system in organizing complex movement sequences from the elements. However, the data also support the theories of Lorenz and Timberlake that there are relatively simple instinctive movement segments that are the elements of more complex movement sequences.

In related research, Teitelbaum and his associates (Teitelbaum, Schallert, De Ryck, Wislaw, & Golani, 1980) used small bilateral brainstem lesions rather than electrical stimulation, and they isolated independent motor subsystems of postural support, locomotion, head scanning, and head orienting that are elements of more complex movement sequences. Teitelbaum et al. (1980, p. 141) hypothesized that in instrumental learning the processes of learning and memory organize the motor subsystems into a goal-directed sequence.

How Animals Learn Movement Sequences

Brown and Jenkins (1968) presented autoshaping, and this caused the distinction to be made that the learning of movement sequences depends on whether the sequence is a stereotyped, species-specific reaction or an arbitrary sequence conceived by a trainer. A hungry pigeon pecking a key for grain is an example of the former, and a trick of a circus animal is an example of the latter. The former is trainable by autoshaping, and the latter by shaping.

Autoshaping

Brown and Jenkins (1968) found that presenting a hungry pigeon with a briefly lighted key, followed by food, elicited key pecking. The hungry pigeon appears to have an instinctive consummatory response sequence that terminates when food is obtained, and the key-food sequence directs the pigeon's consummatory sequence toward the key. Beyond a way of inducing key pecking so that it can serve as the dependent variable in an experiment to follow, autoshaping suggested that Pavlovian conditioning is the answer to whether instrumental learning and Pavlovian conditioning are two kinds of learning or one (Moore, 1973). Instrumental learning is usually described as a response being strengthened

by the reinforcement that follows it, but autoshaping suggests the Pavlovian interpretation that the light, as the conditioned stimulus, is contingently paired with food, as the unconditioned stimulus, and that this elicits food getting as the unconditioned response. The pairing of the light and food produces the emergence of key pecking, a form of food-getting behavior, as the conditioned response to the light. Viewed as biological adaptation, the bird has come to know a new signal that means a food supply can be obtained with the food-getting response. Moore (1973, pp. 174–177) lists five other ways that a pigeon can be led to key pecking, all of which had been rationalized as instrumental learning, and he concluded that all fit the Pavlovian explanation. As persuasive as this Pavlovian analysis is, the analysis and the autoshaping that stimulated it seem limited to instinctive, stereotyped response sequences and bear little on arbitrary movement sequences (Hearst & Jenkins, 1974, pp. 39–40). Shaping, not autoshaping, has been, and continues to be, the way that arbitrary movement sequences are trained.

Shaping

Shaping is the selective potentiation of responses, out of the many a subject can make, to yield the required movement sequence. Skinner (1951, 1953, pp. 91–95), on the training of the pigeon, and Pryor, Haag, and O'Reilly (1969) and Pryor (1975), on the training of the porpoise, are the most informative on the topic. The gist of shaping is that the desired movement sequence has a low probability of occurrence, so it does not occur often enough to be reinforced and strengthened. The procedure is to reinforce movement segments that approximate the desired sequence, and not to reinforce movement segments that are distant from it. With reinforcement the approximations come closer to the desired motor sequence until it is occurring reliably and can itself be reinforced.

Shaping is usually done with primary or secondary positive reinforcement, but punishment can be used also. Positive reinforcement can be used to select a movement segment from the many movement segments that the animal can execute in the situation: punish-

ment may be used to deter segments that are not wanted. Positive reinforcement is the favored training operation in psychology's discussions of this topic, but those who are outside of psychology, like professional animal trainers, are unlikely to be so reluctant about punishment.

Mechanisms of Chaining Movement Segments

Shaping is usually practiced as an empirical enterprise with no theoretical concerns. However, some analysts have pondered the mechanisms by which movement segments are joined into a movement sequence by the positive reinforcement at the end of it.

Selective learning. Thorndike's (1911) theory of trial-and-error, or selective, learning was the first stance on shaping. Discussing his cats that were in a puzzle box and learned to release a latch and get out of the box for food reinforcement, Thorndike (1911, pp. 35–65) decided that the cats' discomfort in the box or their desire for food led to the arousal of instinctive activities, and one of these accidentally led to tripping the latch and, thus, food reinforcement (pp. 67–68). The response that led to escape and reinforcement is strengthened, and so it has an increased chance of occurring on the next trial for further reinforcement and strengthening. Learning of the response is explained by its selection from all of the responses that can occur in the situation. Thorndike's Law of Effect is his theory of how responses are strengthened and weakened in the process of selective learning.

Spence (1956, pp. 26–35), a neobehavioristic theorist, adopted much of Thorndike's (1911) thinking on selective learning, but disagreed on some of the details and was more explicit about others. Spence was less inclined to emphasize the instinctive activities that reinforcement shaped in the situation. Instead, he dealt with both instinctive and learned responses that the experienced animal brought to the situation. Spence saw these responses in a hierarchy of strength, with some more likely to occur than others. If the experimenter chooses a strong response as the one to be learned, then the learning will occur rapidly because the response will occur early, be reinforced and strengthened from the beginning,

and quickly dominate the hierarchy. A response low in the hierarchy will be learned slowly because all responses above it will have to occur first and extinguish through non-reinforcement before the designated response can occur, be reinforced, and dominate the hierarchy. Spence pointed out that the responses in the hierarchy are movement sequences, but that selective learning is not a case of motor learning. The selection is from among movement sequences that are established in the behavioral repertoire. Spence, who endorsed the act as the behavioral unit of law and theory, did not need the same movement sequence to occur each time. Any movement sequence that had the same environmental outcome would suffice (Skinner, 1938).

Thorndike (1911) and Spence (1956) were strength theorists. Reinforcement gives an increment to habit strength, which in turn is correlated with response occurrence. Strength is not a necessary part of selective learning. For Staddon and Simmelhag (1971), reinforcement was a result of selecting one response from all responses that are available in the situation by suppressing unwanted behavior, leaving the desired response dominant. Extinction is a return of the suppressed behavior. The sources of responses can be both instinct and past learning.

Response chaining hypothesis. As an explanation of movement sequences Bain (1868, pp. 330-332) anticipated the response chaining hypothesis. The theory was popularized by James (1890). After the inception of behaviorism (Watson, 1913), the hypothesis remained popular (Guthrie, 1952; Hull, 1952; Skinner, 1934). According to this hypothesis, the response-produced stimuli that result from the occurrence of a movement segment become associated with the next movement segment by a habit connection. When the habit connections have been formed, the movement, once started, runs off as a smooth serial action, with the response-produced stimuli of one segment being cue for the next. The hypothesis is important because it is a senior one, because it appears today in discussions of serial action, and because cognitive views of animal serial action feel compelled to react against it. The response chaining hypothesis can rely on any kind of response-produced stimuli but, on the

basis of his research, Watson (1919) settled the focus on proprioception, which was seen as stimuli in the stimulus-response model. Behaviorism needed stimuli because responses were connected to them, and proprioception served the purpose nicely because it was a necessary accompaniment of any movement. The response chaining hypothesis easily became the reason for movement sequences for behaviorism. Adams' (1968) review included the evolution of behavioristic thinking about the response chaining hypothesis and reactions to it.

An example of behavioristic reliance on the response chaining hypothesis, but with refinements that have evolved since James (1890), can be found in Ferster and Perrott (1968) and Ferster, Culbertson, and Boren (1975). The mechanisms of discriminative stimuli and secondary reinforcement are used to explain how movement segments come to be joined in a complex serial action that has received terminal positive reinforcement. The response-produced stimuli at the end of a segment, with or without delay, are paired with the positive reinforcement at the end of the movement sequence, and so develop secondary reinforcing powers. Alternatively, a stimulus, like a light or a sound, may be given secondary reinforcing powers independently of movement by pairing the stimulus with positive reinforcement, after which it is delivered at the end of movement segments to reinforce them. In whatever manner stimuli are given secondary reinforcing powers, it is hypothesized that their occurrence at the end of a segment is reinforcing for the segment. These stimuli at the end of a segment which reinforce it are also the discriminative stimuli which cue the next segment.

Delay of reinforcement is another way to explain how primary reinforcement at the end of a movement sequence can operate to connect the segments of the sequence (Catania, 1971). Each movement segment is separated from the primary reinforcement by a time delay; the longer the delay, the weaker the strengthening action of the primary reinforcer. With repeated reinforcement even the remote segments become strong enough to occur reliably in their proper place in the chain. The result is a smooth movement sequence.

These behavioristic explanations that rely

on the response chaining hypothesis and use discriminative stimuli and secondary reinforcement, or delay of reinforcement, are trying to handle the difficult issue of how primary reinforcement at the end of a movement sequence strengthens stimulus-response connections that are temporally remote from it. What is the better-than-anecdotal evidence that primary reinforcement, by whatever mechanism, can affect more behavior than the momentary act that is contiguous with it and produces it?

Hawkes and Shimp (1975) reinforced pigeons for executing a temporal pattern. Pigeons were reinforced for either 0, 1, 2, 3, and 4 pecks in successive 1 s intervals, which is an accelerating pattern, or 4, 3, 2, 1, and 0 key pecks as a decelerating pattern. The pigeons learned to perform the patterns with considerable accuracy. Hawkes and Shimp use these data to argue that the act—the response that is contiguous with the occurrence of the reinforcement—should not be the unit of behavior for the laws of psychology. Behavior of a movement sequence that is not temporally contiguous with the reinforcer can be controlled by it and deserves attention also.

Vogel and Annau (1973) presented pigeons with a 4×4 square panel of lights and two keys. The pecking of one key illuminated the light successively downward, and the pecking of the other key moved the light successively in the horizontal direction. A pigeon had to move the light from the upper right-hand corner to the lower left-hand corner of the array with three responses on each of the keys in any order to receive reinforcement. The birds pecked 80% correct in 1,000 to 4,000 trials. Each bird developed a dominant, but not always the same, pattern of responding even though some variability in responding was allowed. Schwartz (1980), using a procedure similar to that of Vogel and Annau, replicated this finding on the stereotypy of a behavior. In an argument that retreats from the act as the response unit for psychology and is sympathetic to the stance of Hawkes and Shimp (1975), Schwartz said that “the dominant sequence has become the unit of behavior with integrity and internal structure” (1980, p. 165). He went on to say that the sequence becomes unitized and so can be a response unit, just as the act is the response unit, and can be

made a function of independent variables. Using the same procedure as before, Schwartz (1981) tested this assertion by focusing on extinction. If a well-learned sequence operates as a unit, then it should be affected as a unit. Schwartz found that the internal patterning of the sequence remained unchanged in extinction for highly trained pigeons, but that latency of the sequence as a whole increased during extinction. That the sequence had integrity during extinction was taken as evidence that it had become a response unit.

Cognitive learning of movement sequences. In its standard form the cognitive view has been suggested as the central half of a central versus peripheral argument; response chaining is the other half. Response chaining, as the hypothesis has been defined historically, is reliance on response-produced stimuli for regulating the segments of a movement sequence, not central factors. It is unlikely that the processing of response-produced visual stimuli would be considered as basically peripheral because they have peripheral receptors, but proprioception is seen in this way because of its peripheral receptors which respond to bodily activity. (Advocates of response chaining have emphasized proprioception more than other sources of response-produced feedback.) The contrasting of response chaining with cognitive determinants of movement can be simplistic, however, because the peripheral dimensions of a response chain can have central factors in their processing just like vision. Not only is there central control of efferent neural activity by motor centers of the brain, and the relating of it to neural activity of spinal origin, but the central processing of afferent information from receptors in the joints, muscles, skin, and vestibular system as well (Wetzel & Stuart, 1976). Moreover, there is an ensemble of information from internal and external sources that must be orchestrated by the brain so the result is organized behavior appropriate for the situation. It is inexact, therefore, to say that response chaining is a peripheral explanation of serial action.

Notwithstanding, the peripheral-central distinction has validity in terms of emphasis because cognitive psychologists have their taproot planted centrally in their quest for states that determine behavior. Memory is of most concern to them, and they seek the structure

that exists there in the form of images, cognitions, thoughts, rules, schemata, plans, and cognitive maps for example. Some cognitive psychologists would admit a role for peripheral variables but they are not interested in them. Those behavioral scientists who appreciate peripheral variables are a spin-off of a physiological interest in the determinants of movement that dates back to the 19th century. This interest is still active in work dealing with the massive array of peripheral machinery of an organism. The main point of a cognitive position, and the motor programming view as well, is that central organization determines movement patterns that reflect them; peripheral factors hardly matter. Motor programming refers to a central agent that regulates a structured movement pattern, although it is not cognitive in the usual sense of higher mental processes. The motor programming view had a strong start in Lashley's (1917) research. Either degradation or elimination of proprioceptive stimuli by accidental deafferentation in the human (Lashley, 1917) or by surgery in the rat (Lashley & McCarthy, 1926; Lashley & Ball, 1929) did not wholly eliminate organized motor performance, and Lashley concluded that motor regulatory agents were primarily central. The motor program has had its advocates (Schmidt, 1975) and its critics (see Adams, 1968, 1976, for reviews).

Modern cognitive psychology is the acknowledged influence on two important articles by Shimp (1975, 1976). Shimp turns to cognitive psychology's interest in memory and its potential for response structure. He questions the act as the behavioral unit on which psychology bases its laws. What if the unit was a structured movement pattern based on a structured entity in memory, rather than the response that is contiguous with the reinforcer? Environmental and response events, either in a short-term or long-term working memory, may be the unit of behavior rather than the response that is contiguous with the reinforcement. Shimp relies on clustering in verbal free recall (e.g., Bousfield, 1953; Tulving, 1962, 1968) as evidence of how events can be structured in memory.

Hulse and his associates (Fountain & Hulse, 1981; Hulse, 1973, 1978, 1980; Hulse & Campbell, 1975; Hulse & Dorsky, 1977, 1979; Hulse & O'Leary, 1982) share Shimp's (1975,

1976) interest in organization and memory. However, their mutual interest was not derived in the same manner. Shimp's interest in organization and memory developed from his reaction to the emphasis that behaviorists have given the act as the behavioral unit; Hulse's interest developed from a reaction to response chaining. Hulse's main experimental situation was a series of trials in which a rat received a different amount of food reinforcement on each trial, and the amounts had a decreasing, increasing, or unsystematic pattern. Hulse found that running times are governed by the pattern of reinforcements. For example, running times will slow down progressively if the amount of reinforcement gets smaller each time.

Hulse (1978) found that rats appear to extrapolate the pattern to values that are implied by it but not previously experienced. They also appear to transfer their running behavior positively to new patterns where the form of the pattern is maintained but the reinforcement amounts differ. It is as if the animal abstracted the pattern and stored it in memory for subsequent use in new situations. According to Hulse the rat is capable of rule learning; the governance of serial action is a cognitive, formal relation, seemingly of a higher conceptual order in memory than the structure that Shimp saw the rat as having. Response chaining is rejected.

Straub and his associates (Bever, Straub, Terrace & Townsend, 1980; Straub, Seidenberg, Bever, & Terrace, 1979; Straub & Terrace, 1981) also endorse the higher order representation of a response sequence or "cognitive chain" (Straub et al., 1979, p. 147) and reject response chaining. On a trial their pigeons learned to peck four differently colored keys in sequence regardless of spatial positions of the colors. All the colors were available simultaneously on a trial. Response chaining requires that the response-produced stimuli of one segment become associated with the next segment, and Straub reasonably contended that the changing spatial positions deny proprioceptive stimuli from serving in this role. The color stimuli could serve the role, with the occurrence of one being the cue for the next, but because they were available simultaneously, they did not provide sequential cues for the responses.

Richardson and his associates (Richardson & Warzak, 1981; Richardson & Bittner, 1982; Richardson & Kresch, 1983) had a somewhat different procedure with their pigeons, and they used their findings to stand by the response chaining hypothesis. They presented the four colors simultaneously, with the positions of the colors changed on each trial, as Straub did, but the color of the correct key brightened each time it was pecked. According to Richardson the brightening of each color was the discriminative stimulus for the next response segment (Richardson & Kresch, 1983, p. 24). Consequently, the response chaining hypothesis could be used to explain serial action. It is possible that the response chaining hypothesis is true under certain circumstances, and Richardson revealed one of them, but there is the inescapable feeling that the concept of discriminative stimuli is diminished by being assumed. Straub et al. (1979, pp. 145–146) were impatient with the kinds of response-produced stimuli that can be invented after the fact to explain serial action.

Capaldi and his colleagues (Capaldi & Verry, 1981; Capaldi, Verry, & Davidson, 1980) have challenged Hulse's (e.g., 1978) conception of serial action, not by defending response chaining but by questioning the degree of abstraction for what memory has stored. Capaldi (1966, 1967, 1971) has had some success in explaining partial reinforcement effects in terms of remembering sequences of reinforced and nonreinforced responses, and he extends his theorizing to include Hulse's findings. He calls his view "multiple hedonic memory" and contends that the memory of a particular amount of reward on a trial becomes the cue for anticipating the reward for the next response of the series. This is done either by retrieving the memory of the reward directly or by generalizing memories of rewarded responses. An entire series of events and their order can be remembered, although Self and Gaffan (1983) conclude that length in memory, although greater than one, is probably limited. Hulse's response is that Capaldi's ideas, and research on them, has failed to embrace the abstract, rule nature of the animals' learning which Hulse has been trying to engage by data and theory. Hulse (1980) calls it "a misdirected effort to achieve parsimony" (p. 690). Whether

it is a misdirected effort, parsimony, or neither, Capaldi's efforts stand with Hulse's in giving the agents of movement sequences a central locus.

The liveliest rejection of response chaining comes from advocates of the cognitive map, who hold that the guiding agent is a space (and perhaps time) analogue which the animal uses to guide movements in the environment. The map is metaphorical and is a way of representing the kinds of information that a subject perceptually learns, organizes, and uses (Menzel, 1978, p. 377). Tolman (1948) is credited with the origin of this view that movement in the environment is basically directed by the products of perceptual learning. The best known of experiments from Tolman's laboratory are on latent learning (Blodgett, 1929; Tolman & Honzik, 1930). Rats that were allowed to wander around a complex maze without reinforcement appeared to learn something about it because they showed positive transfer from the perceptual experience when reinforcement for goal attainment was subsequently given. It would not appear that learning was on the side of response-produced stimuli as response chaining would have, and so the latent learning experiments were controversial. The attempts of other experiments to replicate and explain latent learning in other ways leaned toward Tolman (MacCorquodale & Meehl, 1954, pp. 199–213). Another well-known experiment from Tolman's laboratory that played down the response side and elevated perceptual learning was by MacFarlane (1930). In this study rats had high positive transfer to swimming through a maze after learning it by running and vice versa. The form of the response was not important so the learning must be done elsewhere.

Olton and his colleagues (Olton, 1978, 1979; Olton & Samuelson, 1976), along with Menzel (1973, 1978), have found their research on spatial learning in animals to be compatible with the cognitive map. Olton used a radial eight-arm maze with reinforcement delivered on an arm only if it had not been entered before. The optimum strategy on a trial is to choose each arm only once and to avoid repetitions by remembering arms that had been entered before. Rats became very good at this task. There was no evidence of stereotyped sequences that would suggest response chain-

ing, and so the cognitive map, as a mechanism for a spatial memory that stores information where the animal has been in relation to where it must go, was invoked.

Kohler (1925) said that a chimpanzee could find food that had been buried in its sight 16.5 hr earlier, and Menzel (1973, 1978) amplified Kohler's earlier observation with experiments on spatial learning. To illustrate, Menzel (1973) had one experimenter carry a chimpanzee and walk alongside another experimenter who buried pieces of fruit in a field. The chimpanzee was returned to the cage and then released to find the food; about two thirds of the fruit was efficiently found. The chimpanzee had made no motor movements in original learning that could be recalled at the test, so perceptual learning must have been of events embedded within spatial relations and the test behavior must have depended on memory of them. Tolman would have found these experiments satisfying, along with ethological experiments which seem to call for spatial memory in animals that remember where they have been before in their search for food or their own food hoards (see Olton, 1979, for a survey; Shettleworth & Krebs, 1982).

How Humans Learn Movement Sequences

This article contains similarities between how humans and animals learn movement sequences because animal and human learning have not been independent enterprises in American psychology. Developmental psychologists, as well as investigators of animal behavior, are concerned with organized instinctive behavior in the newborn infant, although it scarcely matches the interest that ethology has shown in the topic. Human instincts are almost self-evident when they are itemized: breathing, tongue movements, swallowing, sucking, looking, hearing, grasping, and movements and posturing of the body would be a typical list. The list is short, and Eibl-Eibesfeldt (1967), an ethologist, believes that it represents scientific neglect, probably because of preoccupation with the massive effects of learning. Whatever the extent of human instincts, analysts of movement in developmental psychology have asked how movement segments at birth and those acquired after come to be the building blocks of

complex movement sequences. It is the same question that their scientific forefathers in early comparative psychology asked. Bruner (e.g., 1973) and Piaget (1952) have been the most influential of these analysts.

Developmental Psychology and the Origins of Movement Sequences

Bruner. The main work of Bruner and his associates on movement learning in the infant is found in a series of articles dating from the 1960s (Bruner, 1969, 1970, 1972, 1973, 1981; Bruner & Bruner, 1968; Bruner & Koslowski, 1972; Koslowski & Bruner, 1972).

Initial movement sequences are formed from diffuse movement patterns that are instinctively given (Bruner, 1973, pp. 2, 6), not unlike the random movements hypothesis. The beginning of a movement sequence (e.g., grasping an object) begins with the infant's intention. Although intentional behavior can be started by an external event, it is inner-directed and persists toward a goal, choosing among alternate paths and continuing until the goal is reached. The parts of an intentional cycle are the "aim, option of means, persistence and correction, and a terminal stop order" (Bruner, 1981, p. 41). Intentional behavior obviously implies prior experience with the world to know about objects and events and their worthwhileness as goals.

After arousal of intention, a loosely organized sequence of response segments occurs. Even though they are poorly executed, purposive moves are made toward the goal that is the center of intention. Attainment of the goal is a matter of problem solving, with reinforcement playing its part in the problem solving and refinement of the movement sequence. Reinforcement does not have a selective function for movement segments, as in a Thorndikian view of selective learning. Rather, it has an informational function that guides the learner in what to do and how to do it. A learning situation has several sources of information, like the eliciting stimulus and response-produced feedback stimuli; reinforcement is one of them. Any given sequence, whether efficient or not, correct or incorrect, is learned by repetition or unreinforced practice, but it is problem solving and aids such as reinforcement that define the movement sequence that is deserving of practice.

Complex movement sequences are a compound of response segments from genetically given and learned sources; they are the subroutines from which more elaborate routines are constructed, to use Bruner's (e.g., 1973) information processing terminology. In turn, these new movement sequences can be the subroutines of even more complex sequences. Thus, the learning of complex movement sequences is hierarchical. The process of acquiring new skills is a matter of constructing new wholes out of existing parts, and so the availability of parts is crucial to the evolution of complex movement sequences.² The mechanisms of assembling the parts are not clear in Bruner's expositions. He speculated that reinforcement is one of the agents (Bruner, 1973, p. 4), and he draws an analogy with language where a child moves to a higher level of syntactic complexity. For whatever concessions that Bruner made to reinforcement, he favored the language analogy where the elements can be assembled and reassembled endlessly into new sequences. Lashley (1951) greatly influenced this kind of thinking.

Bruner and Bruner (1968) used an experiment on infant sucking behavior to show how a response that was initially instinctive can become a central part of intentional, volitional activity and can be used as a building block, a means to a new end. Infants were shown a motion picture, and they learned to control the clarity of the picture by sucking on a pacifier. Behavior which was genetically designed to be at the start of digestive activity was turned to the regulation of a stimulus and the perceptual behavior that was evoked by it.

Piaget. For whatever theme he might have engaged, Piaget (1952) was interested in intelligence, which he considered a mechanism of biological adaptation to the environment (Piaget, 1952, chap. 1). Motor behavior is of no less importance than intellectual behavior because it is a means by which the organism interacts with the environment. Piaget referred to motor behavior as "practical or sensorimotor intelligence" (1952, p. 1), and he distinguishes it from cognitive intelligence. Sensorimotor intelligence dominates a child's first 2 years, with cognitive intelligence emerging toward the end of the second year.

Piaget (1952) cannot be understood without an understanding of his concept of schema.

This is difficult to do because Piaget does not neatly define it. Certainly he does not mean the same thing that behavior theorists have meant by schema for perception or motor recall (e.g., Adams, 1976; Schmidt, 1975). The first useful distinction is that unlike behavior theorists who have perceptual schemata for categorical recognition and recall schemata for categorical response production, Piaget has schema as an action agent that involves both perception and response.

The second useful observation is that schemata are abundant. There is a visual schema, a hearing schema, a sucking schema, a grasping schema, and so on. Although there seems to be a schema for almost anything (which diminishes its scientific power), there is more to schema than its ubiquity implies. Its most important quality is that it is a categorical term, a conceptual entity that applies to a class of behavior. There is a schema for the entire category of grasping actions, not a different schema for every possible form of grasping behavior.

Furthermore, the boundaries of a schema are being continually redefined by new occurrences of behavior in the category, so the outline of a schema remains open. Like concept behavior, one's powers of categorization allow the correct identification of a new instance of a concept, but the occurrence of the new instance might change the capabilities for recognizing instances of the concept.

Finally, schemata are parts that can become organized with experience into superordinate schemata for the regulation of more complex patterns of behavior. Vision and hearing schemata become organized as a child learns to look in the direction of a speaker. The visual and grasping schemata will be organized into a higher order entity for the control of visually guided reaching behavior. The term 'learning' hardly seems to be part of Piaget's scientific vocabulary, but it is in his system nevertheless. Learning is seen as boundaries of a schema change with experience, and as schemata can be parts that organize with experience into a new, holistic schema. This new schema will

² Roles for maturation and physical conditioning would have to be found for a more complete developmental picture of skills.

govern a behavior pattern that is more complex than that which is governed by any of the constituent schemata.

Piaget (1952) is a stage theorist in a time when stages as a way of describing development have decreased in popularity. There are six stages in his conceptualization of sensorimotor development, from birth until approximately 2 years of age. An overview of the six stages suggests how the learning of a movement sequence is explained. As with Bruner (e.g., 1973) and comparative psychologists, behavior in Stage 1 (0 to 1 month) is almost entirely innate. It is these innate reflexes that are the building blocks of more complex behavior. Innate responses like sucking show some refinement at this time, as do appreciation of the objects of sucking. However, a new infant's behavior is regulated mostly by its innate dispositions. Stage 2 (1 to 4 months) shows an increasingly clear emergence of basic schemata like sucking, hearing, seeing, and vocalization as the infant gains in perceptual and motor experience. Stage 3 (4 to 9 months) is exemplified by integration of the visual schema and grasping schema into a higher order schema that allows visual-motor control of the arm and hand. Using visual control, the child will guide the hand to an object and see the consequences of his or her own actions. At Stage 4 (9 to 12 months), there is an increasing organization of schemata, giving the infant a more complex behavioral repertoire. Intentional behavior is evident, where the child clearly has a goal in mind and sets out to accomplish it. Stage 5 (12 to 18 months) reveals an interest in new events, responses, and ways to achieve goals. In Stage 4 the baby is organizing established schemata into new combinations, but in Stage 5 there is almost a creativity as the infant seeks new experiences. Stage 6 (18 to 24 months) sees the emergence of internalized behavior. Instead of exercising schemata explicitly, they now can be exercised implicitly and symbolically. The baby can think about the consequences of pushing a ball and does not actually have to do it. The transition from sensorimotor to cognitive intelligence is beginning.

An example of systematic research on Piaget's (1952) conception of sensorimotor development is by White and his associates (White, 1969, 1971; White, Castle, & Held,

1964), who found Piaget's system an integrating framework for infant behavior. They sought to verify Piaget in the study of visually guided reaching movements, representing development reaching into Stage 3. Although it would appear from their discussion that Piaget's system is still the most integrative one available, they believe that some modification of Piaget's system is required. White (1969) found that the number of schemata that Piaget (1952) had postulated for prehensory development were insufficient to account for the variety of behavior that White observed in his infant subjects, and that more schemata are required. The absence of criteria for schemata makes this lack of agreement understandable.

Piaget's (1952) system offers little regarding the learning of movement sequences. One reason is that development in Piaget's theory of sensorimotor development is a compound of maturation and experience. There seems to be little interest in, or means of, unscrambling the influences of nature and nurture. Another reason is that experience is an omnibus term that is seldom defined in terms of variables that learning psychologists know about or could become interested in. Bruner (e.g., 1973) is closer to the psychology of learning with his concerns about reinforcement and practice, and movement learning as goal-directed problem solving. Investigations of motor learning in developmental psychology would seem to flow more readily from Bruner than from Piaget. However, Piaget's thinking about motor learning is not empty of scientific content because his notion of schema as a cognitive concept is not without researchable substance. Others have claimed that both the perceptual and motor facets of movement are organized categorically, and Piaget, with a twist of his own, has claimed much the same. The findings on recall schema are mixed (Shapiro & Schmidt, 1982), but the most encouraging findings are with children as subjects, so Piaget's position cannot be dismissed.

Hierarchical nature of skills. Neither Bruner (e.g., 1973) nor Piaget (1952) would endorse the random movements hypothesis. Nevertheless, both have hypothesized that complex skills begin in a matrix of unlearned movement segments. This idea is beginning to receive empirical support in developmental psychology. Dodwell and his colleagues

(DiFranco, Muir, & Dodwell, 1978; Dodwell, 1983) and Trevarthen (1975), in their observations of reaching behavior in newborn infants, found movement segments that were characteristic of reaching in much older infants. For whatever resemblances the behavior of newborn infants had to components of mature reaching, the behavior of newborn infants was not considered mature but only having components of mature reaching. Trevarthen (1975) called it "prereaching"; it is an indication of genetic organization that comparative psychology has come to appreciate. In addition, it is a move away from regarding such movements as random and unstructured.

Knowledge of Results

If human reinforcement is stripped of theoretical connotation and is seen merely as the event that follows an instrumental response and affects the probability of its occurrence, then it is no different from reinforcement in animal learning. Essentially this is the way that operant psychology and behavior modification view reinforcement. The therapist's praise of the client for reducing the frequency of compulsive hand washing, giving a retarded child candy after the child manages to get the spoon to the mouth, or giving a rat a food pellet after it presses the bar in the Skinner box are instances of reinforcement because they increase the frequency of a response class. The control of a large catalog of animal and human responses has occurred with this atheoretical, empirical conception of reinforcement. Not surprisingly, it has been influential.

The event that follows an instrumental motor response in human learning and affects its probability of occurrence is called *knowledge of results* (KR). It comes primarily from Thorndike (1927), who viewed KR in a theoretical way, through his Law of Effect, that applied to both animal and human learning.

Thorndike's legacy. Critical surveys of Thorndike's (e.g., 1911, 1927, 1935) ideas and research are available (Adams, 1978; Bower & Hilgard, 1981; Newell, 1976), but it would be worthwhile to review the parts of it that pertain to learning movement sequences.

Thorndike's (1911) research led him to a theory of selective learning and his Law of Effect. His early research centered on animal studies, but later he was concerned mainly with

human learning and education. Thorndike conducted his research on verbal behavior under the aegis of education, but he performed a few experiments on motor learning. One of them (Thorndike, 1927) was defining for the field of instrumental motor learning. Thorndike saw the experiment as a test of his Law of Effect. Blindfolded subjects were asked to draw a line of fixed length, and the experimenter said "right" as a positive reinforcer or "wrong" as a punisher. These subjects should learn, according to the Law of Effect. Control subjects were told nothing after each response. Controls should not learn, according to the Law of Effect, and the possibility that practice repetitions alone are a sufficient condition for learning was accounted for. The experimental subjects learned and the control subjects did not, and Thorndike considered his Law of Effect as confirmed.

As Newell (1976) pointed out, this experiment set the tone for motor learning experiments that followed, until today. The KR is a verbal event that follows the response, and it is a statement of error. "Right" and "wrong," which Thorndike (1927) used as KR, is qualitative error, but quantitative error can be used also. Even Thorndike's line-drawing task has had its persisting influence. Linear positioning tasks are common in the motor learning literature, and they are nothing more than a mechanization of line drawing.

Informational view. Thorndike (1911, 1935) was an associationist, not association between ideas but an association of stimulus and response. The change in behavior called learning was due to a strengthening of the bond, connection, or habit between stimulus and response. Learning was not a cognitive processing of information, where the subject used the reinforcement to discover something about the appropriateness of the response for the situation. Learning was not the consequence of an aware mind actively deciding what to do. Instead, reinforcement, occurring in appropriate relation with the response, worked automatically whether the subject was aware of it or thought about it (Thorndike, 1935, pp. 62-63). A corollary of the associationistic axiom was that the mind is a network of associations, not a cognitive, reflective, conscious entity that is populated with ideas, thoughts, and images.

Although the informational view of motor learning might not have been as thoroughly tested and secured as analysts prefer (Schendel & Newell, 1976), workers in the field have adopted it and have allowed Thorndike's connectionism to become history (Adams, 1971; Newell, 1976). In my closed-loop theory of motor learning (Adams, 1971), I advocated the informational interpretation of KR and gave reasons why Thorndike's view should be set aside. Knowledge of results is error information which the subject receives after a response and uses in the intertrial interval to decide on an improved response on the next trial. A hypothesis is formed, and KR after the next response affirms the hypothesis if the experimenter reports less error than on the previous trial. The subject's success in this process produces the improvement, or learning. Schmidt's (1975) schema theory of motor learning has some conceptual features that are different from Adams's closed-loop theory of motor learning, but his interpretation of KR is similar.

Mechanisms of Movement Segments and Sequences

Response chaining hypothesis. Animal learning has only recently tested and rejected the response chaining hypothesis, but human learning has had no advocacy of the response chaining hypothesis for some time. This article deals with motor behavior, but it would be neglectful not to notice that investigators of serial verbal learning and retention have inquired about mechanisms that control a sequence of responses.

There are two lines of development: One is contemporary and dates back only a few decades; the other connects the past at the beginnings of psychology as a laboratory science. Of contemporary interest is how organizational factors in memory regulate a sequence of verbal responses in immediate recall. A good example is Bower's (Bower, 1972; Bower & Winzenz, 1969) work on how immediate recall is affected by grouping or categorization of verbal elements. The effect of grouping on recall is positive. Bower found theoretical support in the emphasis that Gestalt psychology gave organizational factors in memory (Kohler, 1940), a position conceptually allied to

Shimp's (1975, 1976) thinking about animal movement sequences, which was discussed earlier.

The older line of interest is the serial learning of verbal lists, often called *serial rote learning* to distinguish it from concerns with organizational factors. Investigators of serial rote learning have asked, as the response chaining hypothesis does, how persisting aftereffects of an event control a sequence of responses. They included an appraisal of the response chaining hypothesis among their efforts (for reviews, see Crowder, 1976; Kausler, 1974; Young, 1968).

Ebbinghaus (1885/1964), the founder of research on serial rote learning, suggested that items remote from a particular item in a list had associative strength that was a decreasing function of the number of intervening items or time. He tested to see if nonadjacent items had nonzero associative strength; he concluded that they had. He hypothesized "associative threads" that held the items together. Hull and his colleagues (Hull et al., 1940), who attempted a mathematical theory of serial verbal learning, called the associative threads *stimulus trace*, a more familiar term. The challenge to the Ebbinghaus view came in the position hypothesis, which held that the position of the item, not the item itself, is the functional stimulus in serial rote learning. Some held that both the item and its position were controlling stimuli. Slamecka (1977) presented evidence for the further distinction that response-produced stimuli, in the sense of the response chaining hypothesis, had not been clearly distinguished from item and position as functional stimuli.

The literature of serial rote learning, which covers almost 100 years, is indecisive and often tortuous in the paths that it weaves. It is easy to agree with Young (1968) that the problem of the functional stimulus, and the confounding of stimulus and response that is inherent in serial rote learning, make serial rote learning a dubious vehicle for the understanding of sequential behavior (Young, 1968, p. 145). The response chaining hypothesis is neither accepted nor rejected by the research on serial rote learning; no conclusions have been reached.

The rejection of the response chaining hypothesis by the field of human motor learning

had two forms, both of them conclusive. A major one was Lashley's (1917, 1951) postulation of the motor program; however, his position took on even more provocative dimensions when human motor behavior, primarily speech, became a prime area of analysis. The other was closed-loop theories of motor learning. Some might not see closed-loop theories of motor learning as a rejection of the response chaining hypothesis because they have a conceptual reliance on response-produced feedback, as does the response chaining hypothesis. However, the similarities are shallow. These vectors are covered in the next two sections.

Lashley's legacy. Lashley's (1951) rejection of the response chaining hypothesis had a strong cognitive thrust in concentrating on the relation between the mental dispositions—language—and the motor realizations—speech. Speech is a serial ordering of response units, and according to Lashley a theory of serial action that requires response-produced feedback stimuli from one unit as cue for the next does not fit the facts of language and speech. Infinitely, almost any letter can follow any other of the language, any phoneme any other phoneme, any word any other word, any sentence any other sentence. A theory based on associative linkage misses the mark because it ignores the marvelous flexibility of speech. What, then, determines serial order? Lashley rejected the concept that mental images, intentions, ideas, or imageless thoughts determine order. Word order is different from one language to another, and the immediate translation from one language to another shows that the order in speech is not contained in thought. The ease with which an idea is expressed in many different word orders is more evidence that word order is not contained in thought. Moreover, there is seldom any doubt of what one wants to say but expression of it in speech and writing can have its errors of order.

The climax of Lashley's (1951) article was his assertion that the issue of serial order that he described for speech is an issue for all movement; skilled behavior has the same problems of serial order, and the relation between thought and action, as does speech. In the general sense, it is "the phenomena of the syntax of movement that requires explanation" (Lashley, 1951, p. 122). Lashley's convincing

arguments, and his strong centralist views that had ripened for 34 years (since 1917), have had appeal and have contributed to a weakening of the response chaining hypothesis.

Closed-loop theories of motor learning. Adams (1971) and Schmidt (1975) have articulated theories of motor learning that are closed-loop. Closed-loop systems are error sensitive and error corrective. There is a reference of correctness, and feedback from the system's response is compared with the reference for a determination of error. The system then operates to eliminate the error. Like the response chaining hypothesis, the feedback consequences of response are important for closed-loop theories, but the similarity ends here. The response chaining hypothesis says that response-produced feedback is composed of stimuli that activate the next response segment by virtue of a habit connection, in the best traditions of stimulus-response associationism. Closed-loop theories contend that response-produced feedback is a basic part of an error-sensing and correcting system. The next response segment that is activated is not a function of habit but of error that is sensed.

The research questions that are raised by closed-loop theories are different from those raised by the response chaining hypothesis: What is the nature of the reference of correctness, and how is it learned? Can the human subject sense errors and their magnitude? Does the quality and quantity of response-produced feedback relate to the sensing and correcting of errors? Questions like these have no counterpart in the response chaining hypothesis, and their attractiveness to investigators was a factor in the decline of the response chaining hypothesis.

Contemporary data on human movement sequences and their learning. There is a modern interest in the learning of movement sequences by animals, with the evidence favoring a cognitive view. Corresponding efforts with a theoretical direction, whether cognitive or not, are lacking at the level of human movement sequences (Adams, 1978). There has been a start-up effort, however.

Knowledge of results is the error between a response and a goal. Experimentally, it is almost always in the form of a verbal report to the subject. Knowledge of results about goal attainment is of unquestioned importance; indeed, it has been called the most important

variable for motor learning (Bilodeau & Bilodeau, 1961, p. 250). What it does not do, however, is provide the subject with information on the details of movement sequence in reaching the goal. There are many skills in which the manner of getting there is as important as getting there. For example, a diver's proper entry into the water is admired only if the movements that precede it have the proper form. Without information about the movement sequence that precedes a goal response and KR, the subject is left to work out a suitable response form for approach to the goal. Because of past preoccupation with goal responding and KR about it, with neglect about KR for movement patterns, a compensatory research effort is occurring. It is called *kinematic KR*. An example of the research being done is an experiment by Newell, Sparrow, and Quinn (1983). The subjects had to reproduce a particular force-time function with an isometric control. One group saw their response pattern on an oscilloscope screen superimposed on the desired pattern. Another group had integrated absolute error verbally reported by the experimenter. A third group received verbal KR about the impulse, or peak force. The group with the graphic display that was given full information about form of the movement pattern and could see the errors in it performed the best. A useful review of kinematic KR, with a theoretical orientation, is by Newell and Walter (1981). Rothstein and Arnold (1976) have a practically oriented review of the literature on videotape replay, which is a common technique for a report about movement sequences.

Schwartz (1982) followed up his animal work on the learning of movement sequences (Schwartz, 1980, 1981) with parallel research on human subjects. The task was similar to the one he used with animals. The subject sat in front of a panel with a 5×5 array of lights. The response console contained two response keys, a white light, a red light, and a counter. The rule for the task, or the way to get reinforcement, was to move a light on the panel from the top left position to the bottom right position with four presses of each key before a fifth press occurred on either key. When this was done, the red light came on momentarily as reinforcement or KR, and the counter advanced by one. If the subject failed in the requirement, all lights extinguished and the trial

ended. There were 70 possible sequences of left and right key presses that would result in reinforcement. The subjects learned this task over several sessions, with each subject developing a stereotyped response sequence, just as pigeons do (Schwartz, 1980; Vogel & Annau, 1973).

Schwartz (1980) found that extinction increased the diversity of sequences. The reinstatement of reinforcement after extinction quickly returned the stereotyped response sequence that had prevailed before extinction. Idiosyncratic stereotyped response sequences are not a necessary consequence of reinforcement, because they can be set aside when the experimenter chooses to reinforce a particular sequence. Subjects can be trained to discover the general rule by being instructed to look for it or by being reinforced for its discovery. A subject's behavior is variable rather than stereotyped in the rule discovery period as hypotheses are tested. To use reinforcement as a source of information for an hypothesis on how to make the required movement is the process that defines the informational view of KR.

Schwartz (1982) elevated his findings to a statement on the act as the unit of response for the laws of instrumental learning. He found support from his work on animal learning also (Schwartz, 1980, 1981). The response class that is the act is initially diverse, but as it is reinforced more and more the response becomes stereotyped. Instead of defining response units functionally, as a class, in terms of their effect on the environment, Schwartz defined these stereotyped sequences shaped by reinforcement as units for the laws of instrumental learning. Reinforcement is an established variable for controlling the frequency of instrumental responses, but Schwartz considered the refinement of movement sequences into a stereotyped pattern an even more fundamental function of reinforcement. There is a trace of Guthrie's views in this emphasis of stereotyped movement as a function of reinforcement (Guthrie, 1952; Guthrie & Horton, 1946).

Discussion

I began this article by suggesting that the act as the response unit for the laws of instrumental learning has deemphasized how movement sequences are learned because

movement sequences are not temporally contiguous with the reinforcement and so are dismissed as being inconsequential. Since the 19th century, however, psychologists have not been as insensitive to movement sequences as the concept of the act has been. There have been ideas about where the segments come from and how they are organized into sequences. The ideas and their scientific status have defined the text of this article. In summary, they are as follows.

1. Ethological findings have convinced comparative psychology that the movement sequences of animals are not assembled from random segments that are present at birth. Rather, they come from behavior that has a great deal of coherent structure at birth or with maturation. Learning assembles these instinctive segments into longer sequences. A version of the hypothesis that complex skills are a hierarchy built on a base of random movement segments is at present more active in human developmental psychology than in comparative psychology where it started. However, research on human infant behavior is beginning to indicate that its segments have a degree of organization at birth.

2. The response chaining hypothesis, contending that a movement sequence is assembled by the response-produced stimuli of each segment becoming the cue for the next, with habit as the connecting agent for segments, is dead in both animal and human learning.

3. The view that segments of a movement sequence are cognitively structured is on the rise.

Two final ideas remain to be covered. One is a variant of the question "What is learned?", and human motor learning is used as the context for its discussion. The other is status of the act.

What is Learned?

If movement sequences are always a compound of segments that are in the behavioral repertoire, then there is no such thing as motor learning per se in the sense of acquiring new segments. An individual never learns to make movements that are genuinely new but is always drawing on what is known. Yet, obviously one cannot do what is required in many motor tasks without a protracted period of learning. What, then, is learned?

Much of what passes for human motor learning is not motor learning but the solving of a puzzle that the experimenter has created and which is probably the reason why the informational view of KR exists. The subject is not told what to do, so all of the sources of information that are available must be used to formulate and test hypotheses until the required movement is found. The subject is fully capable of doing what is required but the subject has to discover it. Consider a linear positioning task where the blindfolded subject must learn to make a 10-inch movement. The subject is not told by the experimenter to make a 10-inch movement, but the experimenter does give KR like "right" and "wrong" after each trial. A subject can take more than 100 trials to learn a simple task such as this (Adams, Gopher, & Lintern, 1977; Adams, Goetz, & Marshall, 1972), and yet obviously the subject knew how to make a 10-inch movement at the start. Despite all the studies on linear positioning that have been done as part of studies on motor learning, there is no motor learning among them—only cognitive learning—and the motor response is an indicator of it. Even though motor behavior is central for the task, it is not central to the learning process. Indeed, it is no more central to the learning process than the motor response of button pressing in a concept formation task as a way of designating choice.

It is tempting to make the same analysis of animal learning. Obviously, the rat can press the bar or run the maze but the experimenter does not, indeed cannot, communicate the requirement directly. Reinforcement is provided as an indirect source of information from which the animal must infer the response to be made. Thorndike's (1911) main animal learning task was a puzzle box in which problem solving was exemplified. It seems that many other animal learning tasks that have evolved since then retain problem solving as an essential feature. Thorndike continued with problem solving as the core of learning tasks when he shifted from animal learning to human learning. His influence is visible in current human motor learning (Adams, 1978; Newell, 1976), and the legacy from his animal learning research is part of it.

Suppose, however, the experimenter does not create a problem for the human subjects to solve in a motor learning situation. Suppose

the experimenter makes every effort to inform the subjects of events and response requirements in the task. There is no puzzle, and if the response segments are in the behavioral repertoire, it seems that the subjects would be able to activate them and instantly perform, circumventing the learning. If I am told that the requirement is to move my hand from the typewriter keyboard to the tip of my nose there is no question that I can draw on movements that exist in my behavioral repertoire and do it perfectly in one trial. However, there are many motor sequences that are not instantly executable, even though all of the movement segments are available and the subject knows what to do. A limitation on a cognitive view of skills is that the subject cannot do everything that he or she knows. Lashley (1951) made this point when he said that thought mechanisms do not completely govern action because individuals may know what to say or write and yet make errors of serial order. Other examples of the asymmetry between knowing and doing are easy to find. A popular one is the discrepancy between comprehension and production in language (Clark & Hecht, 1983).

Why cannot a movement sequence always be performed perfectly when the movement segments are fully available in the behavioral repertoire and the subject has a good grasp of what is required? Observational learning (Bandura, 1971, 1977) is a good example of cognitive learning and provides answers to this question. A human subject who is watching a model perform a movement sequence will verbally encode features of the movement and will also acquire a nonverbal perceptual representation which can be called an image. Modeling can produce a substantial amount of learning of a movement sequence, but it is not complete (Carroll & Bandura, 1982). One can always assume that more exposure to the model will complete the learning, but incomplete learning may have more fundamental causes. On the verbal side of the cognitive representation, words are relatively imprecise. Even with richness of connotation, words cannot capture the spatial and timing complexities of many movement sequences. Words are useful in capturing the order of segments and prominent features of them, but certainly they fail to represent important dimensions of movement sequences.

The nonverbal side of the cognitive repre-

sentation may be better at storing spatial and temporal dimensions of movement but little is known about how well nonverbal representations carry dimensions like these. Nonvisual dimensions (e.g., static force or muscular tension) will not be in the representation at all. Even the visual presentation of the movement sequence can fall short if parameters such as angle of viewing are not optimized for communication of information about the movement. Important parts of the movement can be outside of the visual field, and a special effort is required to make them visually accessible for observational learning (Carroll & Bandura, 1982).

Lastly, attention, as a variable for the verbal representation as well as the nonverbal representation, determines what the subject processes and stores, and there is no guarantee with standard modeling techniques that important features of the movement sequence will receive attention. Succinctly, the cognitive representations from modeling may not contain all the details of action.

Undoubtedly, some of the asymmetry of thought and action is due to an inadequate cognitive representation, but this is not what Lashley (1951) meant when he discussed it. The examples he used implied a perfect cognitive representation but imperfect action nevertheless. How can this be? An obvious possibility is that the motor systems of the movement sequence require refinement of their own through learning; cognitive learning is not sufficient. A second possibility is that the coordinating links at the interface of the cognitive representation and the motor systems need to be cultivated through learning. A third possibility is that a cognitive representation at its best contains only salient details of the movement sequence and lacks the data for controlling the fine grain of motor systems (Newell, 1978).

So what is the answer to the question: What is learned? Stripped of problem solving, which has inflated the boundaries of motor learning, what remains that can be called motor learning? There seem to be six processes involved. 1. *A cognitive representation for the patterning of movement segments that comprise a movement sequence.* Some may be tempted to call the cognitive representation a mental model (Gentner & Stevens, 1983), but it is premature to do so. It is easy to draw correspondences

between a cognitive representation and the mental model because there are so many opinions of what a mental model is (Young, 1983, for example, lists eight possibilities). As it is being explored, the concept of mental model is being turned toward education and human factors, where the subject uses knowledge that can be either analogic, quasi-pictorial and visualizable, or abstract in predicting physical processes (e.g., the trajectory of a falling object) or the workings of a machine and the consequences of different machine configurations (e.g., a nuclear power plant). None of the thinking or research on mental models seems particularly useful to movement sequences and their learning, although research on the mental model may make it useful (see Eberts, 1983). In the meantime, it would seem scientifically prudent to use cognitive representation, like Bandura (1971, 1977) did for movement sequences, as a general concept that is not constrained by an implied requirement to describe knowledge about the trajectory of falling objects or the operation of nuclear power plants.

Contemporary theories of motor learning have used a brief initiating agent for a movement (Adams, 1971) or a somewhat longer one (Schmidt, 1975), so why the concept of a cognitive representation? What useful addition does cognitive representation make to theories of motor learning? The answer is the patterned selection of movement segments that comprise a comparatively long movement sequence. Modern theories of motor learning have movements selected and initiated, but they say nothing of how a series of movements is orchestrated as the structure of a long movement sequence. Undoubtedly, the reason for this deficiency is that these theories have relied on research that used simple movements; thus, the theories were not pressed to consider agents for generating more complex movements. The best evidence that addresses the need for the concept of cognitive representation is observational motor learning, which has given attention to the learning of complex sequences with a number of parts.

2. *Coordinating links at the interface of the cognitive representation and the motor systems.* This requirement does not amount to much when the task is easy and the movement segments are fully established in the behavioral repertoire. However, as task complexity in-

creases, the performer may not be able to translate cognition into action without additional learning operations. Knowing is one thing; doing can be another.

3. *Dimensions of movement that are noncognitive.* It is unlikely that a cognitive representation can represent the very motor dimensions of movement like static force, muscular tension, or subtle timing.

4. *Features of movement that are too fine-grain for cognitive representation.* The resolving power of cognitive representations for movement is unknown, but some characteristics of movement may be too subtle for cognitive representation.

5. *Learning of new movement segments as distinct from selecting and ordering segments already in the behavioral repertoire.* From the time when the random movements hypothesis was originated, the position has been held that a new movement sequence is the retrieval and organization of movement segments in store. Items 2 through 4 indicate why this will not always occur even though the segments are in store. Another reason is that the segments do not exist. No amount of cognitive representation can organize and activate segments that are not there. Of the six processes, this one is the most empirically stubborn. It is not clear how to determine that a segment is not in the repertoire and what should be done to train it.

6. *Response recognition.* In closed-loop fashion, humans can detect and correct their own errors (e.g., Adams & Goetz, 1973), and theories of motor learning (Adams, 1971; Schmidt, 1975) acknowledge this capability. These theories rely on the building of a response recognition mechanism by experience with response-produced feedback. However, the extent to which the cognitive representation that generates the response has a role in error detection and correction is also vague; the topic has not been investigated. Intuitively, it would seem that if one knows how to do it, one should be able to use the same knowledge to recognize errors insofar as the cognitive representation contains the pertinent features of the movement sequence. I have argued elsewhere (Adams, 1971) that the logic of error detection and correction requires that the response recognition mechanism be separate

from the response generation mechanism. However, that logic remains to be challenged.

The Act

The idea of the act as the unit of response for the laws of instrumental learning has existed informally since the first instrumental learning experiments on animals, and it has been formally rationalized since 1935 (Skinner, 1935). The act is not theory, but it is the presupposition of theory in specifying how response as the dependent variable should be defined. The act has come under criticism recently (Hawkes & Shimp, 1975; Schwartz, 1980, 1981, 1982; Shimp, 1975, 1976) primarily because it does not consider movement sequences. In defining the act as any member of a response class that produces a reinforcement, the movements that lead to the temporal contiguity of the response and the reinforcer are ignored. This article, in its concern with movement sequences, is critical of the act also. The concept of the act is antithetical to an investigation of movement sequences. It is difficult to treat the act harshly, however. A great deal of understanding about the determinants of learned behavior have been gained under its rationalization. Notwithstanding, the loss of the act's status as the response unit of the laws of instrumental learning is deserved.

The methodological problem with the act is that the reinforcement, which is contiguous with the momentary response configuration that produces it, has influences on a temporally longer behavioral pattern. The domain of shaping has always recognized that terminal reinforcement can be influential for a relatively long movement sequence. However, this was never considered a methodological problem because response chaining, secondary reinforcement, and delay of reinforcement were imposed as explanation, leaving the act intact. Hawkes and Shimp (1975), Shimp (1975, 1976), and Schwartz (1980, 1981, 1982) have questioned whether the effect of terminal reinforcement on a relatively long movement sequence is cause to challenge the act. They urge that the response unit of the laws of instrumental learning be the movement sequence. What is the potential of this idea? The act is entrenched in the psychology of learning and will not be displaced easily, but the act's

methodological problems will not disappear, and so it becomes a duty to examine the worthiness of this challenge.

The main factor that can retard acceptance of a movement sequence as the response unit is the likelihood of slow learning. A sequence can require long training before its defining criteria have been met and can be considered a reliable entity that can be counted. Animal movement sequences can take thousands of trials to cultivate. Human movement sequences, like athletic skills, can require years of training. Unlike bar pressing, a movement sequence does not always exist to be counted from early in learning. Indeed, the criteria for complex skills may never be fully met so nothing will ever exist to count even though a large amount of learning has occurred. This problem of protracted learning might be bypassed with simple, easily learnable sequences that could be counted and be conventional dependent variables, as bar pressing or key pressing have been. However, any sequence is allowable in principle, just as any response that is contiguous with reinforcement is allowable as an act, so the problem of protracted learning is inescapable. The protracted learning problem might be eased by dividing the long movement sequence into segments and shaping each one with terminal reinforcement and then combining the parts into the whole. An obvious difficulty is the combining and its principles. Joining parts could involve extensive learning, so the separate learning of segments does not guarantee the early appearance of the whole sequence for counting.

These problems with the movement sequence as the unit could be resolved if counting, as the fundamental measurement operation, lost status along with the act. Everything would be different if the movement sequence was seen as a skill that is being learned and *error*, with respect to criteria, was considered as the measure of its proficiency. Movement sequences can often have their properties continuously measured, although the counting of discrete errors is appropriate as when a human subject presses the wrong key in a choice reaction time task, or when a rat takes a wrong turn in a maze. There are many kinds of situations that lend themselves to a continuous measure of error. The amount of graded error can be the measure when a human subject is

required to move a limb to a place, or when the deviation from the required displacement of a bar is measured in an animal bar-pressing situation. Space-time accuracy over a relatively long sequence can be measured, similar to the integration of tracking error with respect to time when a human subject is given the task of driving an automobile in the center of a lane at 30 MPH for 5-mi or requiring a rat to hold the center of a straight runway and accomplishing the run in 5 s. Investigators of human learning have been doing these things for a long time. Investigators of animal learning have surfaced only infrequently with research on continuous dimensions of animal behavior. Skinner (1938, chap. 8) explored force and time discrimination in a rat's bar pressing. Notterman and Mintz (1965, chap. 4), extending Skinner's ideas, trained their rats to displace the bar with a specified force of response. The most notable concern with the topic was by Logan (1956, 1960), who built his micromolar theory of behavior upon it. Logan showed, for example, that making delay of reinforcement dependent upon the rat's running speed could make delay a controlling agent for speed. As interesting as these few efforts were, the psychology of animal learning was joined to the act and did not nurture the ideas with additional research.

Will an emphasis on error nullify the data based on counting that learning psychologists have collected over their history? Science is a cumulative process that always saves some of the past and retains it in the body of knowledge that is transmitted from one generation to the next. It is unlikely that a new measurement emphasis would cause findings based on an older emphasis to be set aside because enduring knowledge has been acquired with it, and so reconciliation of the old and new measurement will occur. One way to do it is to notice that the counting of responses like bar presses and key pecks is the frequency of movement patterns whose terminal error is zero. After a relatively long sequence of unmeasured response events in the interresponse interval, the subject terminates the sequence in a bar press or key peck that is defined as the action that is of zero error and correct. Counting in psychology has been an implicit concern with error, and it should integrate with data based on error

of other characteristics of movement sequences. The integration could be helped conceptually by noticing that the act, in allowing membership of all responses of a class, is a categorical conception. There is a renewed interest in categorical behavior, which has rallied around the concept of schema. Consequently, finding a place for data collected under the rationalization of the act could go beyond considerations of measurement. Cognitive learning theorists may find ways to explain data that were collected within a framework that was defined in a time more behavioristic than the present.

References

- Adams, J. A. (1968). Response feedback and learning. *Psychological Bulletin*, 70, 486-504.
- Adams, J. A. (1971). A closed-loop theory of motor learning. *Journal of Motor Behavior*, 3, 111-149.
- Adams, J. A. (1976). Issues for a closed-loop theory of motor learning. In G. E. Stelmach (Ed.), *Motor control: Issues and trends* (pp. 87-107). New York: Academic Press.
- Adams, J. A. (1978). Theoretical issues for knowledge of results. In G. E. Stelmach (Ed.), *Information processing in motor control and learning* (pp. 229-240). New York: Academic Press.
- Adams, J. A., & Goetz, E. T. (1973). Feedback and practice as variables in error detection and correction. *Journal of Motor Behavior*, 5, 217-224.
- Adams, J. A., Goetz, E. T., & Marshall, P. H. (1972). Response feedback and motor learning. *Journal of Experimental Psychology*, 92, 391-397.
- Adams, J. A., Gopher, D., & Lintern, G. (1977). Effects of visual and proprioceptive feedback on motor learning. *Journal of Motor Behavior*, 9, 11-22.
- Bain, A. (1868). *The senses and the intellect* (3rd ed.). London: Longmans, Green.
- Bain, A. (1888). *The emotions and the will* (3rd ed.). New York: Appleton.
- Bandura, A. (1971). Analysis of modeling processes. In A. Bandura (Ed.), *Psychological modeling: Conflicting theories* (pp. 1-62). New York: Lieber-Atherton.
- Bandura, A. (1977). *Social learning theory*. Englewood Cliffs, NJ: Prentice-Hall.
- Bever, T. G., Straub, R. O., Terrace, H. S., & Townsend, D. J. (1980). The comparative study of serially integrated behavior in humans and animals. In P. W. Jusczyk & R. M. Klein (Eds.), *The nature of thought* (pp. 51-93). Hillsdale, NJ: Erlbaum.
- Bilodeau, E. A., & Bilodeau, I. M. (1961). Motor-skill learning. *Annual Review of Psychology*, 12, 243-280.
- Blodgett, H. C. (1929). The effect of the introduction of reward upon the maze performance of rats. *University of California Publications in Psychology*, 4, 113-134.
- Bousfield, W. A. (1953). The occurrence of clustering in the recall of randomly arranged associates. *Journal of General Psychology*, 49, 229-240.

- Bower, G. H. (1972). A selective review of organizational factors in memory. In E. Tulving and W. Donaldson (Eds.), *Organization of memory* (pp. 93-137). New York: Academic Press.
- Bower, G. H., & Hilgard, E. R. (1981). *Theories of learning* (5th ed.). Englewood Cliffs, NJ: Prentice-Hall.
- Bower, G. H., & Winzenz, D. (1969). Group structure, coding, and memory for digit series. *Journal of Experimental Psychology Monographs*, 80(2, Pt. 2).
- Brown, P. L., & Jenkins, H. M. (1968). Auto-shaping of the pigeon's key-peck. *Journal of the Experimental Analysis of Behavior*, 11, 1-8.
- Bruner, J. S. (1969). Eye, hand, and mind. In D. Elkind & J. H. Flavell (Eds.), *Studies in cognitive development: Essays in honor of Jean Piaget* (pp. 223-235). New York: Oxford University Press.
- Bruner, J. S. (1970). The growth and structure of skill. In K. Connolly (Ed.), *Mechanisms of motor skill development* (pp. 63-92). New York: Academic Press.
- Bruner, J. S. (1972). Origins of problem-solving strategies in skill acquisition. In R. Rudner & I. Scheffler (Eds.), *Logic and art: Essays in honor of Nelson Goodman* (pp. 100-126). Indianapolis, IN: Bobbs-Merrill.
- Bruner, J. S. (1973). Organization of early skilled action. *Child Development*, 44, 1-11.
- Bruner, J. S. (1981). Intention in the structure of action and interaction. In L. P. Lipsett (Ed.), *Advances in infancy research* (Vol. 1, pp. 41-56). Norwood, NJ: ABLEX.
- Bruner, J. S., & Bruner, B. M. (1968). On voluntary action and its hierarchical structure. *International Journal of Psychology*, 3, 239-255.
- Bruner, J. S., & Koslowski, B. (1972). Visually preadapted constituents of manipulatory action. *Perception*, 1, 3-14.
- Capaldi, E. J. (1966). Partial reinforcement: An hypothesis of sequential effects. *Psychological Review*, 73, 459-477.
- Capaldi, E. J. (1967). A sequential hypothesis of instrumental learning. In K. W. Spence & J. T. Spence (Eds.), *The psychology of learning and motivation* (Vol. 1, pp. 67-156). New York: Academic Press.
- Capaldi, E. J. (1971). Memory and learning: A sequential viewpoint. In W. K. Honig & P. H. R. James (Eds.), *Animal memory* (pp. 111-154). New York: Academic Press.
- Capaldi, E. J., & Verry, D. R. (1981). Serial anticipation learning in rats: Memory for multiple hedonic events and their order. *Animal Learning & Behavior*, 9, 441-453.
- Capaldi, E. J., Verry, D. R., & Davidson, T. L. (1980). Memory, serial anticipation in pattern learning, and transfer in rats. *Animal Learning & Behavior*, 8, 575-585.
- Carroll, W. R., & Bandura, A. (1982). The role of visual monitoring in observational learning of action patterns: Make the unobservable observable. *Journal of Motor Behavior*, 14, 153-167.
- Catania, A. C. (1971). Reinforcement schedules: The role of responses preceding the one that produces the reinforcer. *Journal of the Experimental Analysis of Behavior*, 15, 271-287.
- Clark, E. V., & Hecht, B. F. (1983). Comprehension, production, and language acquisition. *Annual Review of Psychology*, 34, 325-349.
- Crowder, R. G. (1976). *Principles of learning and memory*. Hillsdale, NJ: Erlbaum.
- Dashiell, J. F. (1928). *Fundamentals of objective psychology*. New York: Houghton Mifflin.
- Delgado, J. M. R. (1965). Sequential behavior induced repeatedly by stimulation of the red nucleus in free monkeys. *Science*, 148, 1361-1363.
- DiFranco, D., Muir, D. W., & Dodwell, P. C. (1978). Reaching in very young infants. *Perception*, 7, 385-392.
- Dodwell, P. C. (1983). Spatial sense of the infant. In A. Hein & M. Jeannerod (Eds.), *Spatially oriented behavior* (pp. 197-213). New York: Springer-Verlag.
- Ebbinghaus, H. (1964). *Memory: A contribution to experimental psychology*. (H. A. Ruger & C. E. Bussenius, Trans.). New York: Dover. (Original work published 1885)
- Eberts, R. (1983). *Internalizing the system dynamics for a second order system*. Unpublished doctoral dissertation, University of Illinois at Urbana-Champaign.
- Eibl-Eibesfeldt, I. (1967). Concepts of ethology and their significance in the study of human behavior. In H. W. Stevenson, E. H. Hess, & H. L. Rheingold (Eds.), *Early behavior: Comparative and developmental approaches* (pp. 127-146). New York: Wiley.
- Eibl-Eibesfeldt, I. (1975). *Ethology: The biology of behavior* (2nd ed.). (E. Klinghammer, Trans.). New York: Holt, Rinehart & Winston.
- Ferster, C. B., Culbertson, S., & Boren, M. C. P. (1975). *Behavior principles* (2nd ed.). Englewood Cliffs, NJ: Prentice-Hall.
- Ferster, C. B., & Perrott, M. C. (1968). *Behavior principles*. New York: Appleton-Century-Crofts.
- Fountain, S. B., & Hulse, S. H. (1981). Extrapolation of serial stimulus patterns by rats. *Animal Learning & Behavior*, 9, 381-384.
- Gentner, D., & Stevens, A. L. (Eds.). (1983). *Mental models*. Hillsdale, NJ: Erlbaum.
- Glickman, S. E. (1973). Responses and reinforcement. In R. A. Hinde & J. Stevenson-Hinde (Eds.), *Constraints on learning* (pp. 207-241). New York: Academic Press.
- Glickman, S. E., & Schiff, B. B. (1967). A biological theory of reinforcement. *Psychological Review*, 74, 81-109.
- Guthrie, E. R. (1952). *The psychology of learning* (rev. ed.). New York: Harper.
- Guthrie, E. R., & Horton, G. P. (1946). *Cats in a puzzle box*. New York: Rinehart.
- Hawkes, L., & Shimp, C. P. (1975). Reinforcement of behavioral patterns: Shaping a scallop. *Journal of the Experimental Analysis of Behavior*, 23, 3-16.
- Hearst, E., & Jenkins, H. M. (1974). *Sign-tracking: The stimulus-reinforcer relation and directed action*. Austin, TX: The Psychonomic Society.
- Hinde, R. A., & Stevenson-Hinde, J. (Eds.). (1973). *Constraints on learning*. New York: Academic Press.
- Honig, W. K., & Staddon, J. E. R. (Eds.). (1977). *Handbook of operant behavior*. Englewood Cliffs, NJ: Prentice-Hall.
- Hull, C. L. (1943). *Principles of behavior*. New York: Appleton-Century.
- Hull, C. L. (1952). *A behavior system*. New Haven, CT: Yale University Press.

- Hull, C. L., Hovland, C. I., Ross, R. T., Hall, M., Perkins, D. T., & Fitch, F. B. (1940). *Mathematico-deductive theory of rote learning*. New Haven, CT: Yale University Press.
- Hulse, S. H. (1973). Patterned reinforcement. In G. H. Bower (Ed.), *The psychology of learning and motivation* (Vol. 7, pp. 313-362). New York: Academic Press.
- Hulse, S. H. (1978). Cognitive structure and serial pattern learning by animals. In S. H. Hulse, H. Fowler, & W. K. Honig (Eds.), *Cognitive processes in animal behavior* (pp. 311-340). Hillsdale, NJ: Erlbaum.
- Hulse, S. H. (1980). The case of the missing rule: Memory for reward vs. formal structure in serial-pattern learning by rats. *Animal Learning & Behavior*, 8, 689-690.
- Hulse, S. H., & Campbell, C. E. (1975). "Thinking ahead" in rat discrimination learning. *Animal Learning & Behavior*, 3, 305-311.
- Hulse, S. H., & Dorsky, N. P. (1977). Structural complexity as a determinant of serial pattern learning. *Learning and Motivation*, 8, 488-506.
- Hulse, S. H., & Dorsky, N. P. (1979). Serial pattern learning by rats: Transfer of a formally defined stimulus relationship and the significance of nonreinforcement. *Animal Learning & Behavior*, 7, 211-220.
- Hulse, S. H., & O'Leary, D. K. (1982). Serial pattern learning: Teaching an alphabet to rats. *Journal of Experimental Psychology: Animal Behavior Processes*, 8, 260-273.
- James, W. (1890). *Principles of psychology* (Vol. 1). New York: Holt.
- Kantor, J. R. (1921). How do we acquire our basic reactions? *Psychological Review*, 28, 328-355.
- Kausler, D. H. (1974). *Psychology of verbal learning and memory*. New York: Academic Press.
- Kohler, W. (1925). *The mentality of apes*. New York: Harcourt, Brace.
- Kohler, W. (1940). *Dynamics in psychology*. New York: Liveright.
- Koslowski, B., & Bruner, J. S. (1972). Learning to use a lever. *Child Development*, 43, 790-799.
- Kuo, Z. Y. (1921). Giving up instincts in psychology. *Journal of Philosophy*, 18, 645-664.
- Lashley, K. S. (1917). The accuracy of movement in the absence of excitation from the moving organ. *American Journal of Physiology*, 43, 169-194.
- Lashley, K. S. (1951). The problem of serial order in behavior. In L. A. Jeffress (Ed.), *Cerebral mechanisms in behavior* (pp. 112-136). New York: Wiley.
- Lashley, K. S., & Ball, J. (1929). Spinal conduction and kinaesthetic sensitivity in the maze habit. *Journal of Comparative Psychology*, 9, 71-106.
- Lashley, K. S., & McCarthy, D. A. (1926). The survival of the maze habit after cerebellar injuries. *Journal of Comparative Psychology*, 6, 423-434.
- Logan, F. A. (1956). A micromolar approach to behavior theory. *Psychological Review*, 63, 63-73.
- Logan, F. A. (1960). *Incentive*. New Haven, CT: Yale University Press.
- Lorenz, K. (1970). *Studies in animal and human behaviour* (Vol. 1). Cambridge, MA: Harvard University Press.
- Lorenz, K. (1971). *Studies in animal and human behaviour* (Vol. 2). Cambridge, MA: Harvard University Press.
- Lorenz, K. Z. (1981). *The foundations of ethology*. New York: Springer-Verlag.
- MacCorquodale, K., & Meehl, P. E. (1954). Edward C. Tolman. In W. K. Estes, S. Koch, K. MacCorquodale, P. E. Meehl, C. G. Mueller, Jr., W. N. Schoenfeld, & W. S. Verplanck (Eds.), *Modern learning theory* (pp. 177-266). New York: Appleton-Century-Crofts.
- MacFarlane, D. A. (1930). The role of kinaesthesia in maze learning. *University of California Publications in Psychology*, 4, 277-305.
- McDougall, W. (1921). *An introduction to social psychology* (14th ed.). Boston, MA: Luce.
- Menzel, E. W. (1973). Chimpanzee spatial memory organization. *Science*, 182, 943-945.
- Menzel, E. W. (1978). Cognitive mapping in chimpanzees. In S. H. Hulse, H. Fowler, & W. K. Honig (Eds.), *Cognitive processes in animal behavior* (pp. 375-422). Hillsdale, NJ: Erlbaum.
- Moore, B. R. (1973). The role of directed Pavlovian reactions in simple instrumental learning in the pigeon. In R. A. Hinde & J. Stevenson-Hinde (Eds.), *Constraints on learning* (pp. 159-186). New York: Academic Press.
- Morgan, C. L. (1896). *Habit and instinct*. London: Arnold.
- Newell, K. M. (1976). Knowledge of results and motor learning. In J. Keogh & R. S. Hutton (Eds.), *Exercise and sport sciences reviews* (Vol. 4, pp. 195-228). Santa Barbara, CA: Journal Publishing Associates.
- Newell, K. M. (1978). Some issues on action plans. In G. E. Stelmach (Ed.), *Information processing in motor control and learning* (pp. 41-54). New York: Academic Press.
- Newell, K. M., Sparrow, W. A., & Quinn, J. T., Jr. (1983). *Kinetic information feedback for learning isometric tasks*. Manuscript submitted for publication.
- Newell, K. M., & Walter, C. B. (1981). Kinematic and kinetic parameters as information feedback in motor skill acquisition. *Journal of Human Movement Studies*, 7, 235-254.
- Notterman, J. M., & Mintz, D. E. (1965). *Dynamics of response*. New York: Wiley.
- Olton, D. S. (1978). Characteristics of spatial memory. In S. H. Hulse, H. Fowler, & W. K. Honig (Eds.), *Cognitive processes in animal behavior* (pp. 341-373). Hillsdale, NJ: Erlbaum.
- Olton, D. S. (1979). Mazes, maps, and memory. *American Psychologist*, 34, 583-596.
- Olton, D. S., & Samuelson, R. J. (1976). Remembrance of places passed: Spatial memory in rats. *Journal of Experimental Psychology: Animal Behavior Processes*, 2, 97-116.
- Piaget, J. (1952). *The origins of intelligence in the child*. London: Routledge & Kegan Paul.
- Pryor, K. (1975). *Lads before the wind*. New York: Harper & Row.
- Pryor, K. W., Haag, R., & O'Reilly, J. (1969). The creative porpoise: Training for novel behavior. *Journal of the Experimental Analysis of Behavior*, 12, 653-661.
- Richardson, W. K., & Bittner, B. J. (1982). Stimulus stringing by pigeons: Effect of feedback for correct selections. *Animal Learning and Behavior*, 10, 35-38.
- Richardson, W. K., & Kresch, J. A. (1983). Stimulus stringing by pigeons: Conditional strings. *Animal Learning and Behavior*, 11, 19-26.

- Richardson, W. K., & Warzak, W. J. (1981). Stimulus stringing by pigeons. *Journal of the Experimental Analysis of Behavior*, 36, 267-276.
- Rothstein, A. L., & Arnold, R. K. (1976). Bridging the gap: Application of research on videotape feedback and bowling. *Motor Skills: Theory into Practice*, 1, 35-62.
- Schendel, J. D., & Newell, K. M. (1976). On processing the information from knowledge of results. *Journal of Motor Behavior*, 8, 251-255.
- Schiller, P. H. (1952). Innate constituents of complex responses in primates. *Psychological Review*, 59, 177-191.
- Schmidt, R. A. (1975). A schema theory of discrete motor skill learning. *Psychological Review*, 82, 225-260.
- Schwartz, B. (1980). Development of complex, stereotyped behavior in pigeons. *Journal of the Experimental Analysis of Behavior*, 33, 153-166.
- Schwartz, B. (1981). Reinforcement creates behavior units. *Behaviour Analysis Letters*, 1, 33-41.
- Schwartz, B. (1982). Reinforcement-induced behavioral stereotypy: How not to teach people to discover rules. *Journal of Experimental Psychology: General*, 111, 23-59.
- Self, R., & Gaffan, E. A. (1983). An analysis of serial pattern learning by rats. *Animal Learning & Behavior*, 11, 10-18.
- Shapiro, D. C., & Schmidt, R. A. (1982). The schema theory: Recent evidence and developmental implications. In J. A. S. Kelso & J. E. Clark (Eds.), *The development of movement control and coordination* (pp. 113-150). New York: Wiley.
- Shettleworth, S. J. (1975). Reinforcement and the organization of behavior in golden hamsters: Hunger, environment, and food reinforcement. *Journal of Experimental Psychology: Animal Behavior Processes*, 1, 56-87.
- Shettleworth, S. J., & Krebs, J. R. (1982). How marsh tits find their hoards: The roles of site preferences and spatial memory. *Journal of Experimental Psychology: Animal Behavior Processes*, 8, 354-375.
- Shimp, C. P. (1975). Perspectives on the behavioral unit: Choice behavior in animals. In W. K. Estes (Ed.), *Handbook of learning and cognitive processes* (Vol. 2, pp. 225-268). Hillsdale, NJ: Erlbaum.
- Shimp, C. P. (1976). Organization in memory and behavior. *Journal of the Experimental Analysis of Behavior*, 26, 113-130.
- Skinner, B. F. (1934). The extinction of chained reflexes. *Proceedings of the National Academy of Sciences*, 20, 234-237.
- Skinner, B. F. (1935). The generic nature of the concepts of stimulus and response. *Journal of General Psychology*, 12, 40-65.
- Skinner, B. F. (1938). *The behavior of organisms*. New York: Appleton-Century.
- Skinner, B. F. (1951). How to teach animals. *Scientific American*, 185, 26-29.
- Skinner, B. F. (1953). *Science and human behavior*. New York: Free Press.
- Skinner, B. F. (1966). The phylogeny and ontogeny of behavior. *Science*, 153, 1205-1213.
- Slamecka, N. J. (1977). A case for response-produced cues in serial learning. *Journal of Experimental Psychology: Human Learning and Memory*, 3, 222-232.
- Spence, K. W. (1956). *Behavior theory and conditioning*. New Haven, CT: Yale University Press.
- Staddon, J. E. R., & Simmelhag, V. L. (1971). The "superstitious" experiment: A reexamination of its implications for the principles of adaptive behavior. *Psychological Review*, 78, 3-43.
- Straub, R. O., Seidenberg, M. S., Bever, T. G., & Terrace, H. S. (1979). Serial learning in the pigeon. *Journal of the Experimental Analysis of Behavior*, 32, 137-148.
- Straub, R. O., & Terrace, H. S. (1981). Generalization of serial learning in the pigeon. *Animal Learning & Behavior*, 9, 454-468.
- Teitelbaum, P., Schallert, T., De Ryck, M., Wishaw, I. Q., & Golani, I. (1980). Motor subsystems in motivated behavior. In R. F. Thompson, L. H. Hicks, & V. B. Shvyrkov (Eds.), *Neural mechanisms of goal-directed behavior and learning* (pp. 127-143). New York: Academic Press.
- Thelen, E. (1981). Rhythmic behavior in infancy: An ethological perspective. *Developmental Psychology*, 17, 237-257.
- Thorndike, E. L. (1911). Animal intelligence: An experimental study of the associative processes in animals. *Psychological Review Monograph Supplement*, 2(4, Whole No. 8). In E. L. Thorndike (Ed.), *Animal intelligence: Experimental studies* (pp. 20-155). New York: Macmillan.
- Thorndike, E. L. (1927). The law of effect. *American Journal of Psychology*, 39, 212-222.
- Thorndike, E. L. (1935). *The psychology of wants, interests and attitudes*. New York: Appleton-Century.
- Timberlake, W. (in press). The functional organization of appetitive behavior: Behavior systems and learning. In M. D. Zeiler & P. Harzem (Eds.), *Advances in analysis of behavior: Vol. 3. Biological factors in learning*. Chichester, England: Wiley.
- Tinbergen, N. (1951). *The study of instinct*. Oxford, England: Clarendon.
- Tolman, E. C. (1920). Instinct and purpose. *Psychological Review*, 27, 217-233.
- Tolman, E. C. (1922). Can instincts be given up in psychology? *Journal of Abnormal and Social Psychology*, 17, 139-152.
- Tolman, E. C. (1948). Cognitive maps in rats and men. *Psychological Review*, 55, 189-208.
- Tolman, E. C., & Honzik, C. H. (1930). Introduction and removal of reward, and maze performance in rats. *University of California Publications in Psychology*, 4, 257-275.
- Trevarthen, C. (1975). Growth of visuomotor coordination in infants. *Journal of Human Movement Studies*, 1, 57.
- Tulving, E. (1962). Subjective organization in free recall of "unrelated" words. *Psychological Review*, 69, 344-354.
- Tulving, E. (1968). Theoretical issues in free recall. In T. R. Dixon & D. L. Horton (Eds.), *Verbal behavior and general behavior theory* (pp. 2-36). Englewood Cliffs, NJ: Prentice-Hall.
- Valenstein, E. S., Cox, V. C., & Kakolewski, J. W. (1970). Reexamination of the role of the hypothalamus in motivation. *Psychological Review*, 77, 16-31.

- Vogel, R., & Annau, Z. (1973). An operant discrimination task allowing variability of reinforced response patterning. *Journal of the Experimental Analysis of Behavior*, 20, 1-6.
- von Holst, E., & von Saint Paul, U. (1973). On the functional organization of drives. In E. von Holst (Ed.), *The behavioural physiology of animals and man*. (Vol. 1, pp.220-258). Coral Gables, FL: University of Miami Press.
- Watson, J. B. (1913). Psychology as the behaviorist views it. *Psychological Review*, 20, 158-177.
- Watson, J. B. (1914). *Behavior: An introduction to comparative psychology*. New York: Holt.
- Watson, J. B. (1919). *Psychology from the standpoint of a behaviorist*. Philadelphia, PA: Lippincott.
- Wetzel, M. C., & Stuart, D. G. (1976). Ensemble characteristics of cat locomotion and its neural control. *Progress in Neurobiology*, 7, 1-98.
- White, B. L. (1969). The initial coordination of sensorimotor schemas in human infants—Piaget's ideas and the role of experience. In D. Elkind & J. H. Flavell (Eds.), *Studies in cognitive development: Essays in honor of Jean Piaget* (pp. 237-256). New York: Oxford University Press.
- White, B. L. (1971). *Human infants: Experience and psychological development*. Englewood Cliffs, NJ: Prentice-Hall.
- White, B. L., Castle, P., & Held, R. (1964). Observations on the development of visually-directed reaching. *Child Development*, 35, 349-364.
- Young, R. K. (1968). Serial learning. In T. R. Dixon & D. L. Horton (Eds.), *Verbal behavior and general behavior theory* (pp. 122-148). Englewood Cliffs, NJ: Prentice-Hall.
- Young, R. M. (1983). Surrogates and mappings: Two kinds of conceptual models for interactive devices. In D. Gentner & A. L. Stevens (Eds.), *Mental models* (pp. 35-52). Hillsdale, NJ: Erlbaum.

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