Chapter 2

Skill acquisition

John Annett
University of Warwick

The defining characteristics of skill (or a skill) are that it is behaviour which is (a) goal-directed, (b) well organised and economical of effort, and (c) acquired through training and practice rather than being innate or instinctive. While the term skill has traditionally been used to refer to motor rather than verbal or intellectual performance, the use was broadened by Bartlett (1958) to encompass cognitive skills such as thinking and problem solving and by social psychologists (e.g. Argyle, 1969) who refer to social skills, particularly to those of the manipulative sort such as persuasion.

This extended usage, while perhaps illuminating some aspects of cognitive and social psychology, widens the concept of skill to the extent that a single theory of acquisition is unlikely to be able to account for all cases. For example, should a theory of skill acquisition apply equally to the learning of football and a foreign language? Probably not. If truly comprehensive concepts of skill and skill acquisition are required, then they would be that *a skill is a behavioural solution to a particular class of problems,* and *skill acquisition is the process of discovering the solution.*

ANALYSIS OF PROBLEMS

The idea that a skill is a solution to a problem illuminates some of the most important features of skill acquisition. At first, the novice may have a goal with no appropriate behaviour in the repertoire which leads directly to the goal. This is true of both physical and intellectual skills. Riding a bicycle without falling off is a problem if you have never done it before just as much as is solving a differential equation or selling an icebox to an eskimo. Calling a skill 'a solution to a problem' then directs our attention to the analysis of the problem—that is, how to model successful performance. Instead of simply thinking of learning as a matter of honing existing behaviour to a higher level of efficiency, we ask questions about the nature of the processes underlying performance and what might happen to them in the course of learning. The following examples illustrate the point.

Modelling skills

The first example is a theoretical model of bicycle riding by Doyle (1988) which describes the physical dymanics of the rider–machine–terrain system as shown in Figure 2.1. The model describes the sensory information available to the rider and a description of the outputs necessary to keep the system within certain goal tolerances, for example upright, moving forward, avoiding obstacles, and so on. The control system is represented as three nested feedback loops which control lateral displacement, heading change, and roll rate respectively. The 'problem' for the novice cyclist is that the physical dynamics of the machine lead to instability (a high roll rate) when the handlebars are turned to change direction and this is also strongly affected by the forward velocity. Novices typically travel slowly when instability is higher than at faster speeds, and are anxious about avoiding obstacles. However, applying the wrong correction to the handlebar can introduce instability, especially at low speeds, and so the initial stages of learning can be difficult.

The skilled cyclist has learned just how much pressure to apply and how long to apply it to the handlebar to produce an appropriate turn without falling. This can be best learned by practising in an area free of obstacles and by inducing a sufficiently high forward velocity to increase the natural stability of the machine. When this basic skill of controlling the roll rate has been acquired, the learner can devote more attention to the skills of controlling direction, some of which are probably already in the repertoire having been

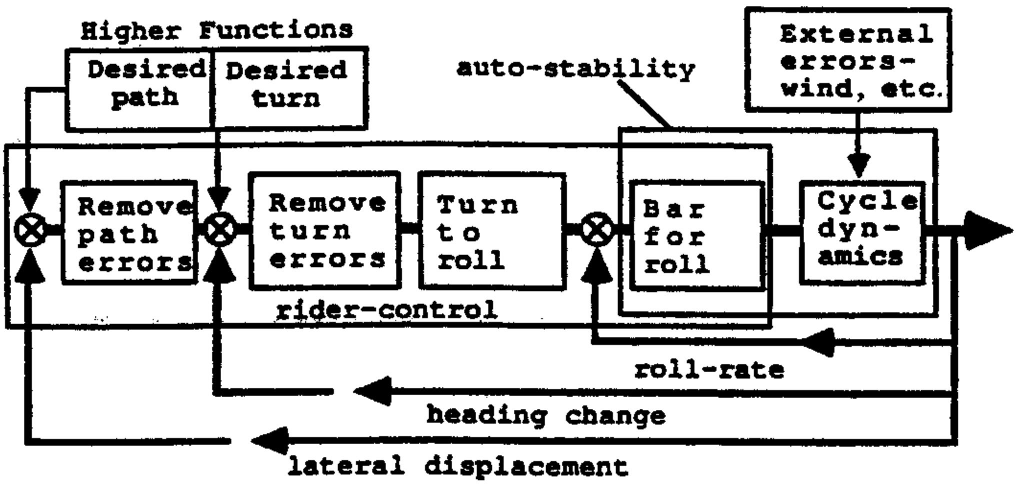

Figure 2.1. The essential control functions in bicycle riding. After Doyle, (1988). Reproduced by permission of Elsevier Science Publishers.

learned at least in part through the normal processes of navigating through foot traffic.

A very different kind of skill, typing, has been modelled by Rumelhart and Norman (1982). Learning to copy type means learning to make fast accurate finger movements in response to a series of visual stimuli (i.e. the text). The problem for the learner is that whereas normal visual reaction time is of the order of 190 milliseconds, the average interval between keystrokes of a moderately skilled typist is about 60 milliseconds. The model, which was actualised as a computer simulation, describes how information about the text and about the current positions of the hands in relation to the keyboard might be processed.

As shown in Figure 2.2, text input is first 'read' by a perceptual system which identifies words. The mechanism for instructing individual finger movements comprises two parts, individual 'keypress schemata' and a servo system which relates finger position to locations on the keyboard. The keypress schemata are activated by rules which specify their order, such that in typing 't-h-e' the schema for 'h' is inhibited until 't' has fired. The levels of activation of the schemata are subject to small random variations so that sometimes this sequencing mechanism fails, producing errors such as 'hte' instead of 'the'. The perceptual interpretive mechanism can operate in parallel with a low

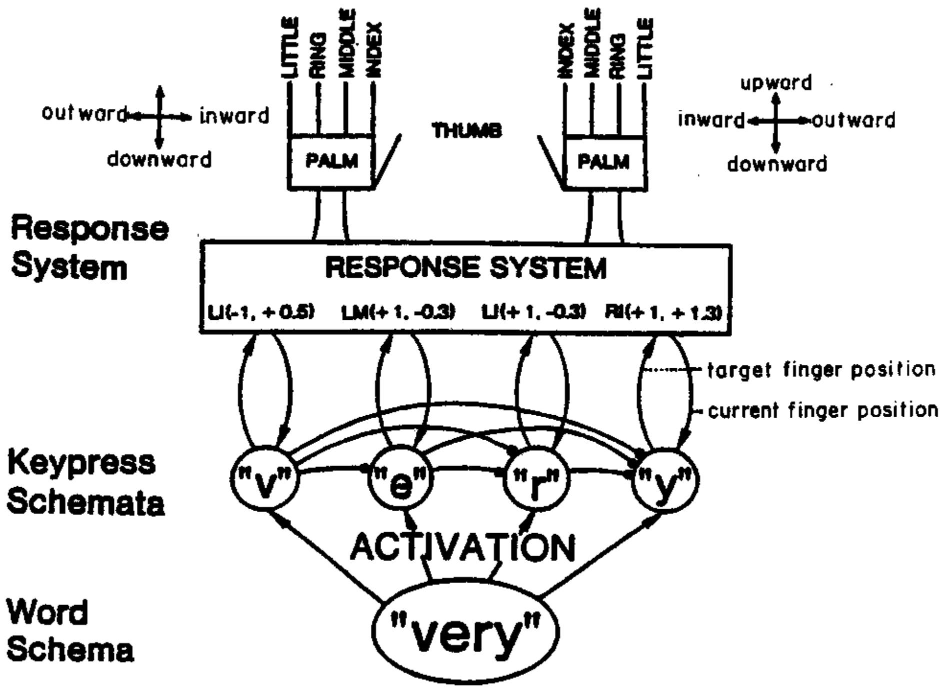

Figure 2.2. Rumelhart and Norman's (1982) schema model of typing. Lines ending in arrows indicate activation while those ending in solid circles indicate inhibition. Reproduced by permission of the authors.

level servo-mechanism which simply indicates the proximity of each finger to its appropriate key and adds its input to the activation of that schema when the finger is sufficiently near. The simulation, although on the author's admission still far from comprehensive, gives a plausible account both of typing speeds and of the kinds of errors made by typists. By indicating how the speed problem might be 'solved', the model also provides an interesting commentary on the role of practice. Just as in the cycling example, a low level semi-autonomous feedback loop is critical to the performance of a skill which also includes other elements (e.g. reading and spelling) that have been acquired independently. Practice with the keyboard is presumably necessary to keep an accurate internal representation of the layout required by the position servo.

Analysing tasks

In both of these examples, the theoretical model of the skill is expressed in information-processing terms: that is, the model specifies what sensory or input information is necessary for performance and how it is used or translated into action. This information can be selected (i.e. attended to or ignored), it can be stored in long- or short-term memory, and it can be translated into action by production rules of the form 'if input = x then execute action y'. This is not to say these processes are introspective or that the skilled performer is able to explain which inputs are being attended to or to state the precise rules by which input is turned into action. Nevertheless a psychological theory of the skill in such terms can lead to hypotheses about what sources of information the learner must attend to, what must be retained in memory, and what transformation (or production rules) must be acquired. With a well-articulated model expressed in these terms, it then becomes possible to specify what it is the trainee must learn to do in acquiring a given skill and to set up an appropriate training programme.

The process of modelling a task in this way is known by the generic term *task analysis* and a number of specific techniques have been developed in the past few decades. The method developed by Annett and Duncan (1967), and Annett *et al.* (1971) called Hierarchical Task Analysis (HTA) was based on the work of R.B. Miller (1953) and draws on the structural analysis of behaviour due to Miller, Galanter and Pribram (1960). The central idea is that the performance of a skill can be analysed into a nested hierarchy of operations and sub-operations. An operation is a statement of (a) the conditions under which an action (b) is appropriate and (c) the condition indicating successful completion of the action.

The top level of the hierarchy is represented by a very general statement of goals, for example 'drive a car safely from A to B'. At an intermediate level of description we have subtasks such as steering, gear changing, and procedures such as starting and stopping. Each of these can in turn be analysed into more detailed components. If necessary the analysis can be continued down to the level of describing precisely what cues the operator should use and exactly which actions will be adequate in a specific manoeuvre such as reversing around a corner. John Patrick gives an example of HTA and further discussion of the technique in Chapter 5.

This kind of analysis enables the trainer to specify effectively what aspects of the skill problem the trainee still has to solve and to provide various kinds of assistance. The kinds of problems faced by a learner may be quite varied. In some cases, the learner who is having difficulty in performing a task simply needs information, such as where to find a component, or knowledge of a rule, such as what to do when a particular symptom appears. In other cases it may be helpful to draw attention to particular sensory cues whose significance is not obvious to the novice. In still other cases, when speed or precision is needed, the training solution may be more practice of one particular task component. It is inherent in task analysis that the identification of learning problems is, in practice, the shortest route to identifying the type of training required. HTA is effective because it directly addresses the basic question of what exactly is learned when skill is acquired. We now go on to consider the kinds of experimental evidence of skill learning found in the research literature.

EVIDENCE OF LEARNING

Early studies of skill acquisition, such as those by Bryan and Harter (1897, 1899) in morse telegraphy, Book (1908) on typewriting, and Swift (1910) on ball tossing, all followed the methods pioneered by Ebbinghaus (1885) for the study of verbal learning and memory in which the number of trials of repetitive practice was the principal independent variable. In motor skills, speed and accuracy of performance were the common dependent variables: just as Ebbinghaus used simplified stimulus materials, so also relatively simple motor responses formed the basis of studies of skill acquisition.

Quantitative changes

Changes in individual variables, for example time to complete a task or execute a movement, probability or magnitude of error, the amount of 'work' accomplished per attempt or per unit time, and other numerically specifiable variables, can all be taken as indicators of skill acquisition and plotted on a learning curve. Learning curves are typically negatively accelerated, suggesting a progressive process, such as trial and error, in which each trial provides an opportunity to strengthen some aspect of the response or stimulus–response connection, or to eliminate some less than ideal feature.

These early researchers attached considerable significance to learning curves and relatively flat sections known as *learning plateaux*. Bryan and Harter interpreted plateaux discovered in morse code learning as evidence for the development of a habit hierarchy in which the trainee learns first to deal with single letters and later with letter strings, a process which only yielded practical benefits when mastered to some point signalled by the end of the plateau. In the 1940s and 1950s the widespread interest in the learning theories of Thorndike and Hull focused attention firmly on repetition and practice and the mathematical properties of the learning curve. Actual performance was, according to Hull's (1943) theory, a joint function of *habit strength* and a number of other factors, principally the current level of motivation or *drive*, and the amount of *inhibition* which builds up as a function of the repetition of an action. Habit strength, or pure learning, was thought to be a function of the number and value of *reinforcements* or rewards following a response to a given stimulus. The shape of the observed learning curve was thus determined by schedule of reinforcement, for example reinforcement on every trial or less frequently, and the distribution of practice, since rest between trials theoretically allowed inhibition to dissipate. Practice variables, such as the frequency of reinforcements, distribution of practice trials, practice on part of the whole task, and the regulation of task difficulty, were important features of skill acquisition research until the 1960s when information-processing concepts began to displace those of behaviourist 'learning theory' associated with Thorndike and Hull.

Snoddy (1926) showed in studies of mirror tracing that learning curves for relatively simple tasks which are practised many hundreds or thousands of times produce a linear function when the logarithm of a performance score is plotted against the logarithm of number of practice trials. This finding has been repeated in a number of instances of skills which comprise short routines repeated many times, such as cigar rolling (Crossman, 1959) and a choice of reaction tasks (Seibel, 1963) and many others (Newell and Rosenbloom, 1981). Newell and Rosenbloom have argued that this log–log linear law of learning can be accounted for by a single basic learning process which they refer to as *chunking*. Chunking basically means that initially separate processes are grouped together and dealt with as simple wholes. The grouping of letters into words observed by Bryan and Harter is an example of chunking, but others could include any well-learned routine that can be recalled or produced as a unit, not having to be assembled from separate parts.

It is probably unwise to draw firm conclusions about the nature of basic learning processes from the shape of the learning curve. Such curves are simply plots of actual performance, and as Hull suspected, may derive from a number of different underlying or intervening variables including motivation and fatigue as well as physical features of the task, such as the minimum cycle time of a machine, which may limit performance.

Other researchers (Woodrow, 1939; Adams, 1957; Fleishman, 1960; Jones, 1970) have used the methodology of individual differences to seek evidence of underlying processes in the interrelationships between many different variables and how they change as a function of practice. Fleishman and Hempel (1954) related performance on a Discrimination Reaction Time Task to performance on other psychomotor and intellectual tests and found that the proportion of variance accounted for by a factor specific to the task and to some other 'motor' factors tended to increase as a function of practice while 'intellectual' factors measured by verbal and spatial tests tended to account for progressively less of the total variance as a function of practice. The conclusion, attractive to some theorists but heavily criticised by others (e.g. Adams, 1987), was that cognitive processes become less important and motor processes specific to the task become more important as learning progresses.

Qualitative changes

Evidence of skill acquisition can also be derived from qualitative changes in performance, including changes in technique, the adoption of less effortful and more effective working methods, simplification of movement patterns and the grouping together of actions and stimulus inputs, changes in error patterns, changes in attention, and the ability to cope with additional simultaneous tasks and to resist the deleterious effects of fatigue and stress. Some of these changes may occur slowly but some, for example a change of method, can be abrupt. Touch typing provides an example of a qualitative change in technique, which incidentally leads to quantitative improvements. Touch typists can achieve fast speeds because they do not have to look at the keyboard between keystrokes. According to Long (1975, 1976) they carry out a visual check on the keyboard only about three times per 1000 keystrokes, although the number goes up with difficult text material. Resistance to the detrimental effects of environmental stressors such as heat or noise was shown by Mackworth (1950) to be related to level of skill already achieved by practice. Errors tend to occur in a variety of tasks, including morse telegraphy and vigilance (monitoring) tasks, which are carried out under adverse conditions such as high temperature or being a long time on watch. Mackworth found 'the better the operator the smaller the decrement in his accuracy of work. . .'. However, we cannot be sure whether these effects are due to greater skill *per se* or to becoming adapted to the stress itself since Mackworth's high ability subjects were experienced in both respects. Nevertheless, changes in skill due to practice remains an attractive hypothesis in view of other evidence such as the effects of extended practice on increasing the ability to do two things at the same time (cf. McLeod, 1977; Spelke, Hirst and Neisser, 1976).

THEORIES OF SKILL ACQUISITION

Research into the processes of skill acquisition recognises two fundamental paradigms, *practice* and *instruction*. In practice experiments the learner is active and makes repeated attempts to perform the task. Under instruction, by contrast, the experimenter (or trainer) provides verbal instruction, text illustrations, models and simulations, advice and correction, while the learner remains essentially passive, at least during instruction. Practice is readily quantified in terms of number of discrete trials or amount of time spent, at least if the central features of the task remain constant. Tracking tasks (in which the learner attempts to align a cursor with a moving target or keep a moving indicator at a constant reading) and linear positioning tasks (in which the subject learns to make a discrete movement of a specific extent) have been the most popular experimental situations for studying the effects of practice. However, almost any task in which uniform responses are required can serve to show how a single feature of performance, such as speed or accuracy, changes as a function of number of trials. Instruction, on the other hand, does not provide such a simple experimental paradigm. Information presented in text material, verbal instruction, or a demonstration is not easily quantified and is at best treated as a binary (all-or-none) variable. For example, in an early experiment, Judd (1908) investigated the effect of instruction in the principles of refraction on the transfer of a dart-throwing task between targets seen through different depths of water. One group of subjects receiving instruction did not learn the initial adjustment any faster than those who received no instruction; however, these subjects were better able subsequently to learn to hit a target at a different depth. The problem with this sort of experiment is that we do not have any independent measure of the quality of the instruction and hence it is not easy to generalise from a single set of results. Maybe some other instructor could explain the principles of refraction more simply or perhaps another might not do it so well. Thus we clearly cannot conclude simply from Judd's experiment that instruction will always improve transfer but not acquisition.

The distinction between practice and instruction also reflects the assumption that quite different processes may be responsible for learning. Practice provides the opportunity for a uniform, slow, incremental, and essentially automatic learning process, while instruction achieves its effects through cognitive processes which may include rapid changes in knowledge of relevant information, in perceptual organisation, or in response strategy. One of the fundamental research issues is whether separate theories of acquisition are needed to account for the culturally transmitted, vicariously acquired aspects of skill on the one hand and the personal effects of individual practice on the other. Fitts (1964) characterised skill acquisition as a progressive shift of the control of performance from cognitive to non-cognitive processes. In his three-phase theory of skill acquisition the initial cognitive phase is dominated by learning rules and procedures and other items of factual knowledge by means of instruction or trial and error. The second and third stages are dominated by practice during which stimuli become connected with responses (the associative phase) and performance becomes increasingly independent of cognitive control (the autonomous phase). The Fitts sequence, which has been echoed by many writers (Rumelhart and Norman, 1978; Annett, 1986; Anderson, 1982, 1987), implies that not only are different training techniques appropriate at different stages in learning but also different processes underlie the learning that does occur. Fitts did not claim that sharp distinctions could always be made between these three phases, but for the purpose of this review, the main topics will be discussed in the order suggested by the Fitts sequence.

Cognitive processes

The first or 'cognitive' phase which is dominated by verbal instruction and demonstration is seen 'as a first step in the development of an executive program' (Fitts and Posner, 1967, p. 12). Behavioural elements which are already in the learner's repertoire are selected and rearranged, and other changes may occur, for example changes in attention, particularly focusing on relevant cues. Items of factual information relevant to the task may also be learned. The two principal classes of cognitive methods are *verbal instruction* and *demonstration*. The central theoretical problem is how information received 'passively' by these two methods gets translated into the capability for action. It is primarily this issue which divides 'cognitive' from 'behaviourist' theories of learning: however, as Adams (1987) pointed out, theory in this aspect of motor learning is somewhat underdeveloped. Figure 2.3 represents my own attempt to formulate the problem of the relationships between cognitive and non-cognitive processes in a way that suggests lines of empirical research. The top of the diagram represents two classes of inputs—words and actions. (Other classes of input such as stimuli arising from non-human sources are not shown.) The central part of the diagram represents internal processes and the bottom represents the output, either words or actions. The left-hand side of the diagram represents the non-verbal domain of actions while the right-hand side represents words, or the verbal domain.

The central part of Figure 2.3 is divided into four areas, the top pair representing receptive and interpretive processes and the bottom pair representing productive processes. They are represented separately in recognition of the fact that production can be inhibited; however, as we shall see, a fairly intimate relationship between receptive and productive processes can be assumed.

A number of different experimental paradigms, represented as routes

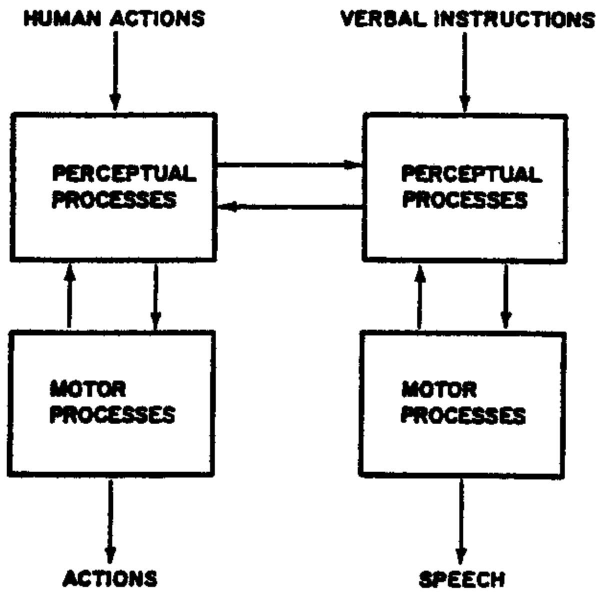

Figure 2.3. The 'action-language bridge'. Hypothetical relationships between verbal and non-verbal systems involved in imitating and describing actions and in following verbal instructions.

through the system, are indicated by arrows. Most, but not all of these, are from the top down, in the conventional direction of perception → action. Some routes proceed from the top straight down, with the output mode matching the input mode (i.e. actions are imitated and words are repeated), while some cross over between the action and verbal systems. In particular, verbal instructions can be translated into actions, a familiar instructional paradigm; but perceived actions can also be translated into words. The latter route corresponds to the less familiar task (at least as far as experimental research is concerned) of giving a verbal account of actions. The most obvious case is the radio sports commentator, but generally we are talking of the production of eyewitness accounts.

Verbal instruction

Before going on to discuss what can be gained from the model, I must defend the two important assumptions: (a) that action and language systems can be regarded as separate; and (b) that representational and productive systems are separable. The first assumption is justified in terms of neurological evidence that the ability to learn and perform skilled actions is to a large extent independent of verbal learning and memory. I have reviewed the evidence in detail elsewhere (Annett, 1982, 1985, 1990), but the most striking examples are found in cases of ideo-motor apraxia such as the patient described by Geschwind and Kaplan (1962). This patient was able to follow verbal instructions, such as 'show me how you use a hammer', with the right hand but not with the left, although the latter was not paralysed. Furthermore, when a hammer was placed in his left hand the subject was able to demonstrate its use. This patient was found on post-mortem examination to have extensive damage to the corpus collosum such that verbal instructions, which are processed in the left hemisphere, could not be passed to the right hemisphere, which controls the left hand. Translation between verbal and non-verbal codes is undoubtedly more complex than making a simple anatomical connection; but as this example shows, traffic between the two systems across what I have called the *action–language bridge* deserves more attention than it has received. A number of studies (Annett, 1985, 1986, 1990; Bainbridge, 1979; Berry and Broadbent, 1984, 1987, 1988) have confirmed that it is often difficult to explain in words how a skilled action is performed. In the case of a familiar skill, such as tying a bow, it is clear that the translation from actions to words is normally mediated by a process of self-observation. Subjects typically rely on 'going through the motions' either overtly by making gestures or by generating images which they are then able to describe. There are also clear limitations on what the subjects are able to describe. Bow tying, for example, is typically described in terms of actions or outcomes, such as making a loop, rather than as the pattern of finger and hand movements which are actually employed. In other words, the representations stored in memory generally do not provide kinematic detail but are expressed in terms of objectives to be achieved, for instance the knot is pulled tight. Looking at the action–language bridge from the opposite view, namely that of turning verbal instructions into actions, it appears that again kinematic detail is not the most successful form of communication about actions. Coaches typically use metaphor and imagery to convey complex movement information. For example a squash coach of my acquaintance describes the stance to be adopted to receive service as 'like a Red Indian on the warpath'. This produces a comprehensive image of an alert stance with feet apart and knees bent, and the right hand raised holding the racket at about shoulder height.

In learning a complex skill, such as flying, a great deal of factual information is also acquired. Sometimes factual information may have direct relevance to actual performance. For example, skill in detecting and correcting infrequently occurring errors in process control tasks typically requires an extensive store of factual information as well as the use of efficient search strategies (Bainbridge 1979, 1988). Even sport skills require knowledge of the rules. Skilled games players typically exhibit a rich factual database of 'declarative' information (Starkes, 1987), also French and Thomas (1987) have demonstrated that as children gain proficiency in a sport skill so their factual knowledge of the game increases. Of course it does not necessarily follow that simply because theoretical instruction often precedes practice that learning *is* the conversion of declarative knowledge into procedural knowledge (as proposed by Anderson, 1987). The ability to perform a skill and the verbal knowledge relating to it may develop in parallel. It may even be the case that some kinds of verbally accessible knowledge only emerge after the skilled performer has the leisure to reflect on his own or other people's performance. As noted earlier, some aspects of motor skill may never have been, and may never be, translated into declarative knowledge.

The model in Figure 2.3 also distinguishes between not only verbal and non-verbal processes but also representational and production processes in both modalities. The representational processes are involved in perceiving and imagining; in other words, what is proposed is a pair of mechanisms (one verbal and one non-verbal) that are involved in the interpretation of incoming data, speech and actions, respectively. The production processes are involved in the execution of speech and motor acts, but they can be inhibited when engaged in inner speech or imaginary action. This close association between representation and production is a feature of some recent theories of speech perception and production (e.g. MacKay, 1982) but has not previously been suggested in relation to action perception and production. The unique aspect of my proposal (Annett, 1982) is that there is a specialised action perception system which serves the purpose of interpreting the actions of others and also of organising our own. The work of Johansson (1973) and others such as Cutting (1978) illustrates the way in which movement and intention can be efficiently extracted from minimal visual data. A few point light sources attached to various parts of the body are sufficient to allow an observer with no other cues to identify human movement and even to deduce unseen features, such as the nature of the load carried and the sex of the actor. These findings are consistent with the existence of a finely tuned system such as one might expect of a social species where the behaviour of others is one of the crucial sets of environmental information needed for survival. This is precisely the kind of mechanism which is needed as a basis for understanding imitation and observational learning.

Demonstration and observational learning

The dominance of behaviourists theories of learning has inhibited the development of theories of the cognitive processes underlying imitation. Bandura's theory (Bandura, 1977, 1986) covers the broad span of observational learning, including circumstances in which the learner will adopt another individual as a model. (Social learning theory is discussed in detail by Latham and Crandall in Chapter 9 of this volume.) A complete theory of observational learning must, however, account for the mechanism by which perceived action is coded in such a way as to be capable of generating action. The model outlined in the previous section suggests that encoding of action information is a specialised process closely linked to action production. An action is 'perceived' when a 'description' has been achieved. A 'description' not only identifies an action but also at the same time is a recipe for producing that action. Since the work of Bernstein (1967) has become more widely known through 'ecological' writers such as Turvey (1977) and Turvey and Kugler (1984), it has become increasingly apparent that the central representation of actions rarely if ever involves detailed patterns of instruction to individual muscles. The 'description' of an action is more like a programme which, when given appropriate data concerning current conditions, can produce a particular result, such as moving an object from one place to another.

If successful imitation of an action requires the learner to acquire a description of the action, then it is worth looking at factors which might prevent or distort this process. Conjurers who practise sleight of hand operate largely by misleading the audience into misinterpreting what they see. Even without the intention to deceive, however, the demonstration of a skill may fail to provide the observer with an adequate description. Sheffield (1961), in a systematic review of teaching by demonstration, drew attention to the importance of breaking down the demonstration of complex skills into 'natural' units. Most individuals seem to be able to do this intuitively. For example, video recordings of subjects first tying a bow and later *demonstrating* how to tie a bow actually make characteristically different kinds of movement (Annett, 1990). In demonstrating the task, the 'natural units' (picking up the loose ends, twisting them together, etc.) tend to be separated out into discrete sections with pauses between them, and the movements are not simply slowed but are often amplified in scale. For instance, in demonstrating the final step in which the knot is pulled tight, the pulling action is made in an exaggerated form which can be two or three times the amplitude of the normal action.

There is a growing body of evidence that action perception typically involves identifying and encoding specific features. Newtson (1980) suggested that skilled observers monitor movement features, particularly encoding 'break points' where a particular feature undergoes a significant transformation. In these experiments, subjects were shown filmed movement sequences and were required to detect whether or not short sections of the record lasting up to 0.5 seconds had been deleted. Over half the deletions that occurred at break points were detected as against less than one-third of those occurring between break points. Whiting, Bijlard and den Brinker (1987) studied the use made by subjects of a model in the acquisition of a complex dynamic skill resembling slalom skiing. The subjects stood on a 'ski simulator', consisting of a platform mounted on a pair of bowed rails. The platform was attached to springs which tended to hold it in a central position and the subjects' task was to move the platform rhythmically to the left and right against the springs using the legs and trunk with an action pattern similar to skiing. Two groups of subjects practised over five daily sessions: while one group was allowed to discover an efficient technique for performing the task, an experimental group was shown a 1.5 minute video recording of an expert working on the apparatus during training. The opportunity to observe the skilled model enabled subjects in the experimental group to achieve a more fluent performance than control subjects, although they did not differ in either the amplitude or frequency of movement. Whiting *et al.* argued that fluency is the best measure of skill since it represents efficient use of effort. They also pointed out that this result was obtained without subjects necessarily imitating all aspects of the model's performance. It appears they had been able to extract some higher order feature of the movement pattern and apply it to their own productions.

Many skills, for instance sport skills, are not easily broken down into distinct elements or performed at significantly slower speed, so it is difficult for the unskilled observer to produce an adequate description. It is here that video recordings or even diagrams accompanied by verbal explanation may enable the observer to 'see' how the skill works and to form an adequate description. There is some evidence that skilled performers do have more detailed perceptions of actions. Imwold and Hoffman (1983) found that experienced instructors recognised more components in recordings of handsprings than novices. Vickers (1988) showed that when visual fixations were recorded, expert gymnasts were more likely to attend to the relevant body parts as well as being able to make more accurate judgements about filmed performances. These findings in motor learning compare with those of de Groot (1965) and Chase and Simon (1973) in relation to chess indicating that skilled players perceive and retain more information about the distribution of pieces on a chessboard than do novices and non-players.

Detailed differences between the performances of the model and the imitator can also show how the action has been 'described'. A demonstration which contains enough elementary descriptions to exceed short-term memory will result in an unsuccessful attempt, typically because one or more units are omitted. Depending on the nature of the task this may well result in overall failure. Smyth and Pendelton (1989) have recently shown that short-term memory for discrete meaningless movements is only about four items. A typical error made by young children is to produce a mirror reversal of the demonstrated movement and this too may be interpreted as a failure in producing the appropriate description. Imitation of tongue protrusion and hand gestures has been recorded in neonates (Meltzoff and Moore, 1977) and imitation is well documented in other species (van Lawick-Goodall, 1971, in chimpanzees and Kawai, 1965, in Japanese macaques). Despite this early onset of ability to imitate, children do improve in their ability to perceive and reproduce action patterns. Thomas, French and Humphries (1977) testing girls aged 7 and 9 on a stabilometer skill found that the younger children gained less benefit from seeing a model than older children, who also were better able than the younger ones to use the model as a source for correcting the partially established skill.

Video recordings have been used both to provide demonstrations by skilled models and also to provide feedback to learners from their own performances. Burwitz (1981), reviewing the use of demonstrations and video tape recordings in teaching gymnastic skills, found the results were sometimes disappointing and offered a number of possible reasons. Sometimes the time delay between performance and viewing the recording may be too long and critical features of the model's performance may not be easy to see. Scully and Newell (1985) confirmed that video demonstration was more effective with the Bachman ladder task in which the successful technique was clearly discernible than with a ball rolling task in which the difference between successful and unsuccessful trials was not apparent from the gross kinematic pattern visible in the recording.

To summarise, observational learning of skills has been a somewhat neglected research field, no doubt because it did not fit any of the popular models of skill acquisition. However, a theoretical framework is beginning to emerge to which the encoding of motor information is the key. The perception of action appears to be selective in a way which makes sense. As social organisms, we are naturally interested in interpreting the actions of others and so have developed a sensitivity to a variety of features of body movement. The attractive hypothesis is that the ability to perceive an action pattern is closely coupled with the ability to reproduce it, but before this hypothesis can be adequately tested we need to learn more about the perception and encoding of movement information and how it varies with age and experience.

Practice

Practice is the *sine qua non* of skill acquisition, but the mechanism by which repetition is effective is still a matter of speculation. The negatively accelerated learning curves noted by the earliest workers or the log–log linear function relating performance to the amount of practice identified by later workers (Crossman, 1959; Seibel, 1963; Newell and Rosenbloom, 1981; Welford, 1987) suggest an underlying process which is both homogeneous and slow, such as laying down a memory trace or engram. Theories are traditionally divided into two camps, namely those that suggest that exercise or repetition *per se* is effective and those that emphasise the selective possibilities offered by repeated trials. Exercise theorists propose that each learning trail offers an opportunity to acquire some new information or to strengthen associations between stimuli or between stimuli and responses, while selection theorists propose that trials offer the opportunity to strengthen some aspect of behaviour and/or weaken others. It is of course possible to propose both kinds of process. For instance, Rumelhart and Norman (1978) suggested that new knowledge could be accumulated ('accreted' was their term), and that processes dealing with new information might also be 'tuned', that is selectively adjusted to take account of new information, or even 're-structured' (see also Cheng, 1985), which is a more drastic kind of reorganisation than tuning.

One of the early attempts at an information-processing account of skill acquisition by Annett and Kay (1956, 1957) began with the proposition that there is a fixed capacity to process stimulus information. Since information is proportional to stimulus uncertainty, the apparent improvement in the rate of processing information, which comes with increasing skill, might be accounted for by a progressive reduction in stimulus uncertainty. This comes about as the learner builds up an internal model of the environment and particularly of the non-random relationships between events. These also include events brought about as a consequence of previous actions. For example, after practice the flight of a dart becomes progressively more predictable from feedback received during the course of preparing for and executing a throw. Two specific predictions follow from the theory, one concerning part-task training and one concerning the withdrawal of knowledge of results. The first prediction is paradoxical in that it suggests that tasks which have high sequential interdependency are best learned initially in parts. The reason for this is simply that when a novice practises such a task, his own error will feed forward to generate a more unpredictable environment than would otherwise be the case. The second prediction is that knowledge of results can only be safely withdrawn without performance loss when it has become effectively redundant. When performing a task the operator receives a stream of feedback signals and, as a result of repeated trials, will build up a probabalistic model of sequential dependencies between them. On the basis of the model, events relating to the final outcome are predictable from events occurring earlier in the sequence. Hence, an experienced golfer knows before the swing is complete if the shot it likely to be good.

Among other 'elementary' learning principles which have been proposed to account for the log–log linear relationship are 'chunking' (Newell and Rosenbloom, 1981) and discrimination (Welford, 1987). The idea of grouping emerged from Bryan and Harter's studies of morse telegraphy in which trainees progressed from transcribing each letter as a separate item to identifying whole words as units. The modern term 'chunking', originating from Miller's (1956) notion of chunks of information, suggests that processing resources, such as memory, are limited in the number of separate chunks which can be held in store or actively processed at any one time. A chunk is any set of mental entities (or 'expressions'), perceptual or motor, which can be dealt with (e.g. stored in memory) as a single unit. Chunking is an automatic process, and learning progresses as elementary chunks become grouped together as larger chunks. Newell and Rosenbloom (1981) argue that such a process offers a good fit to the empirical power law of learning in a variety of perceptual–motor and cognitive tasks.

Starting with data from reaction time studies, Welford (1987) has challenged the goodness of fit to a log–log linear plot and proposed an alternative mechanism based on signal detection theory. He suggests that in choice reaction time tasks, which in the Cambridge tradition of Craik and Hick have been taken as a paradigm of skill, practice has the effect of making the connections between stimuli and responses more distinctive. The parameter *d'* (*dee prime*), which is taken as a measure of perceptual discrimination independent of *beta* (the subject's response criterion), increases linearly with the square root of the number of times the stimulus has been presented. Practice, therefore, increases the signal-to-noise ratio of stimuli. Since making one response rather than another is seen as depending on stimulus discriminability, reaction time is progressively reduced by repeated practice.

Theoretical claims for particular fundamental processes made on the basis of goodness of fit should be treated with caution, particularly when, as in this case, it is quite hard to find data which do not, at least approximately, fit a log plot. As I have previously pointed out (Annett, 1985), however attractive a quantitative model at first appears, the experimental data themselves often present problems by the absence of good estimates of origin and asymptote. A truly satisfactory theory would have to account for not only the fit of the learning curve but also changes in response time distributions (Long, Nimmo-Smith and Whitfield, 1983). Welford (1987) in fact claimed a better fit of choice reaction time data to a linear/square root plot provided that a discontinuity is recognised between the first eight or nine trials and later trials. He explained that there may be an initial 'restructuring' cognitive process followed by a slower motor learning process based on improved discrimination resulting from repeated experience.

A different kind of theory based on the effects of pure 'exercise' was proposed by MacKay (1982). His theory is particularly relevant to serial skills of which speech production is an example. The production of a coherent speech string is seen as being controlled in a hierarchical fashion. At the top of the hierarchy, a sequence of ideas is generated taking account of both semantic and syntactic rules. This feeds down into a phonological system that organises the ideas into sound patterns. Finally, activation feeds down into a muscle movement system which directly controls the vocal apparatus. This hierarchy is activated from the top down through a network of connections that determine which items are activated and in what order. The learning principle is that when a node is activated by receiving stimulation from other nodes it is 'primed', that is to say, its potential for firing is raised. A particular node will fire when its priming exceeds that of all the other nodes in its domain. The theory predicts a number of phenomena found in serial production skills. For instance, sequence errors are seldom random but, like Spoonerisms, appear to result from failures in the sequencing mechanism. Most substitution errors occur within the same category, that is noun for noun, verb for verb, and so on. The model also makes some interesting predictions relating to improvements in performance resulting from rehearsing a skill in imagination rather than overtly.

Mental practice

Mental practice deserves a brief digression since learning effects cannot be attributed to any external consequences, such as rewards and punishments, nor can they be attributed to the effects of repeated external stimulation. Change can only take place through the medium of some internal trace or representation of the skill. Mental practice has a long history, William James (1890) having observed that we learn to skate in the summer and swim in the winter. A substantial number of studies (see reviews by Corbin, 1972; and Richardson, 1967) have shown that rehearsing a skill in imagination can result in improvements in performance which, although usually less marked than those achieved by physical practice, are nonetheless greater than those found after no practice or rest.

A number of theories advanced to account for mental practice effects were compared by means of a meta-analysis by Feltz and Landers (1983). A classic theory, illustrated by the electromyogram (EMG) studies of Jacobson (1932), is that mental practice evokes activity in the motor output system and, although this is largely suppressed, it is detectable in EMG records. According to the theory, this activity is enough to generate minimal kinaesthetic feedback through which some learning is mediated. While EMG activity has been reported in mental practice, for example Suinn (1972) with the mental rehearsal of skiing, there is no firm evidence that this activity is related to the specific response pattern being learned as opposed to generalised activation. A more plausible theory, supported by Feltz and Landers's (1983) meta-analysis, is that mental practice permits the rehearsal of cognitive processes associated with task performance. Tasks which involved learning mazes and other sequential skills were found to be much more likely to produce significant improvements with mental practice than others, such as balancing tasks, which were more purely motoric in character. However, a revised analysis (Feltz, Landers and Becker, 1988) failed to confirm this conclusion.

Some results by Johnson (1982) (see also Annett, 1985) illustrate the specifically cognitive nature of mental rehearsal in one kind of motor task. Johnson used a linear positioning task to demonstrate the well-established phenomenon of interference in short-term motor memory. If, between learning to make a linear movement of a particular extent and having to recall it, the subject is required to make a movement of a very different extent (say twice as long), then the recalled movement is overestimated. Johnson first showed that instructions to imagine making a movement twice as long produced the same bias in recall as an interpolated overt movement. Then, by adding a variety of secondary tasks to the instruction to imagine making the movement, he showed that only tasks which involved spatial imagery disrupted the effect. Most interestingly, subjects required to tap on the table with the hand they were simultaneously imagining moving laterally retained the imagery-induced bias. Thus the effect of imaginary movement was shown to be completely isolated from any muscular activity.

MacKay's theory, as well as accounting for features of skill acquisition referred to above, also offers an account of mental practice. MacKay (1981) showed that the sub-vocal repetition of novel sentences gave practice effects which were, if anything, larger than those obtained by overt practice. The argument is that uttering a novel sentence will involve the activation of an unfamiliar pattern of nodes representing the semantic and syntactic structure of the sentence. Since activation leads to priming, these nodes will be rendered more likely to fire in this new pattern and even relatively few trials will have an effect on the speed with which the whole sequence is run off. The lower level nodes controlling the muscles to produce familiar morphemes are not much affected even by overt practice since they are already well rehearsed and hence optimally primed. MacKay's results certainly fit the predictions and may be taken as supporting the 'cognitive' explanation of mental practice, but attempts by Beladaci (see Annett, 1988) to extend these predictions to typing have met with less success. According to the theory, skilled typists who, by definition, have had a great deal of practice at the perceptual–motor level should show relatively greater benefit from mentally practising unfamiliar sequences of words. This prediction was not confirmed nor was the prediction that mental practice would bring about more improvement with nonsense material that meaningful sentences, and so this ingenious theory must be considered as still 'not proven'.

Feedback and knowledge of results

The paradigms of instruction and practice come together in one of the central research issues in skill acquisition. Practising with knowledge of results (KR) provided by an instructor, either directly or through some automatic scoring device, is one of the most effective ways of acquiring a skill (see reviews by Bilodeau, 1969; Annett, 1969; Salmoni, Schmidt and Walter, 1984). The central theoretical question about KR is what is the nature of the underlying learning process? Is it, as Thorndike (1933) and other behaviourists such as Skinner (1953) would claim, an automatic process (reinforcement) by which stimuli are linked to responses; or is it, as most later theorists (Annett, 1969; Adams, 1971; and Schmidt, 1975) maintain, a cognitive process in which feedback information is used to modify responses or to store up useful information?

Before attempting to answer this question let us briefly review the basic experimental paradigm and typical results. Thorndike (1932) developed the most widely used experimental technique. The subject is required to attempt to draw a line, or make a simple linear movement of some specified extent, usually without the aid of vision or other intrinsic cue. After each attempt, the subject is given KR, which may simply be 'right' or 'wrong' or may be more detailed such as '*N* units of distance too long—or too short'. Sometimes more complex tasks, such as tracking, are used. KR may be in the form of some continuous signal, such as a light or sound indicating 'on target', or in the form of a time-on-target or an error score provided at intervals between trials. In even more complex tasks, KR might come in the form of scores relating to more than one aspect of performance such as the kinematic pattern of the response.

Thorndike's theory specified that the reinforcing effects of KR in strengthening the stimulus–response bond were best served when KR was provided immediately after the relevant response and on as many occasions as possible. While results generally fit this pattern, there are complications. Strict temporal contiguity can be violated without detrimental effects on learning provided the interval between response and feedback is not filled with other activities (Lorge and Thorndike, 1935). Some experiments have confounded delay of KR with intertrial interval but Bilodeau and Bilodeau (1958a), in a comprehensive study independently varying the interval between response and KR and post-KR delay, demonstrated decisively that delay of KR as such was of no consequence.

According to reinforcement theory the strength of an S–R bond is directly proportional to the number of reinforcements but in animal studies (e.g. Ferster and Skinner, 1957) partial reinforcement schedules (i.e. giving a reward on some trials but not on others) make for slower acquisition but also promote greater resistance to extinction. The principle was applied by analogy to tracking training by Houston (1947) and by Morin and Gagné (1951). These experimenters used a gunnery simulator in which the trainee tracks a target projected on to a screen and receives artificial feedback in the form of a filter that makes the target change to red whenever a hit is scored. The results confirmed the prediction that on removal of KR, by analogy with experimental extinction, the hit score declined less rapidly for those subjects on a 50% schedule as compared with those receiving the red filter with every hit. However, the filter treatment seems to have acted as a 'crutch' to performance rather than as an aid to learning since performance tended to decline rapidly once it was remmoved. Hence, its value as a training aid was seriously in question. Again Bilodeau and Bilodeau (1958b) carried out the definitive study using a version of the line drawing or linear positioning task with KR given after every trial or every 2, 3, 4, 5, or 10 trials. They found that the rate of learning was directly proportional to the absolute number of trials on which KR was provided but unfortunately did not report on performance after withdrawal of KR. Annett (1959) in a similar task found that error on withdrawal of KR was less, but not significantly so, if subjects had received KR on alternate trials only.

Salmoni *et al.* (1984) rightly complained that many investigators have paid more attention to acquisition than retention following the withdrawal of KR or transfer to the non-KR condition. Annett and Kay (1957) pointed out that what really counts is what happens when the learner transfers from practising on the training device, or from under the watchful eye of an instructor, to the actual task. The provision of temporary KR is only of value if the trainee can subsequently get all the information needed from cues which are intrinsic to the task. Figure 2.4 shows some of the principal feedback loops involved in performing a task such as tracking or discrete linear positioning. The upper level represents the human operator, in this context the learner, and the second level down represents the machine or experimental apparatus. The arrows represent feedback loops which are active during or following a response. At the top level, numbers 1, 2 and 3 are internal feedback loops concerned with the central control of attention (1), proprioceptive control (3) and exteroceptive control (2). In a positioning task, for example, loop 2 would represent the situation in which the learner can see whether his response is correct as he makes it. All these feedback loops are *intrinsic* to the task, hence the term *intrinsic feedback.*

If the learner is operating a machine then feedback typically comes via loop 4, that is through a display such as a moving pointer or some other artificial indicator. Loop 2 may not be available. For example, in driving a car there are two sources of feedback concerning speed: the changing visual field through the windscreen (loop 2) and the speedometer (loop 4). Both normally provide intrinsic feedback but we tend to rely on the speedometer when precise control of speed is important; it is not required that we learn to judge speed

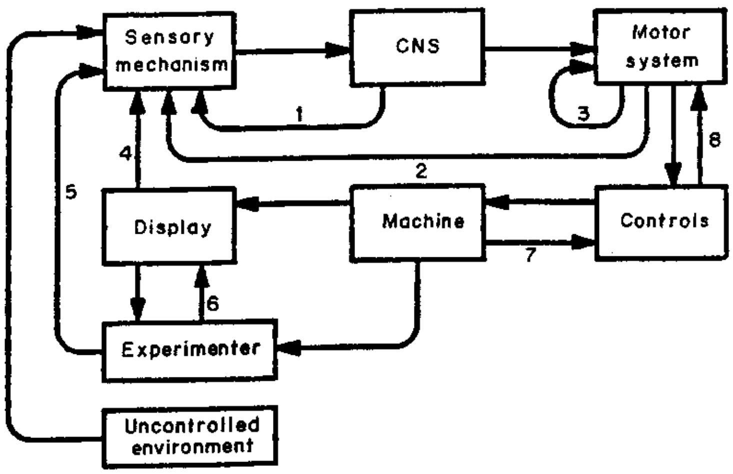

Figure 2.4. The principal feedback loops involved in the control of a machine.

without the help of the instrument. At the bottom of the diagram, the experimenter (or instructor) can form an additional feedback loop, either substituting for the display by giving verbal feedback or embellishing it with additional comments on standards, hints on corrective strategies, and so on. This feedback loop (5) is *extrinsic* if it is only used as a temporary measure during training, and so it is important that the trainee not only learns *from* it but also learns *to do without* it. Dependence on extrinsic feedback may be reduced by having to do without it on some trials, by being 'weaned' from it, or by the instructor drawing attention to feedback which is intrinsic to the task—whether it be proprioceptive or some exteroceptive source of feedback. Further experimental confirmation that these techniques give better retention than providing extrinsic feedback on every trial comes from studies by Ho and Shea (1978) and by Schmidt *et al.* (1989).

The rejection of the reinforcement interpretation of KR depends not just on the failure of a number of predictions to do with the frequency and timing of KR (see Annett, 1969, for a detailed review), but on how well an information-processing account fits the data. The main evidence comes from findings that acquisition is enhanced by the information content of KR where the amount of information is a function of the precision or amount of detail in KR. Trowbridge and Cason (1932) showed that telling subjects not only if their responses were right or wrong but also the direction and extent of error enhanced both acquisition and retention of a discrete line-drawing task. Although this result supports the information-processing viewpoint, a number of subsequent studies (Annett, 1959; Bilodeau, 1953; Bilodeau and Rosenbach, 1953; Green, Zimilies and Spragg, 1955) failed to confirm that learning and retention bore any simple relationship to the degree of precision in KR. In linear positioning tasks, giving directional KR is beneficial to a point but further increases in precision typically fail to yield benefits. The data in Figure 2.5 from Annett (1959) show fairly typical results for a positioning task. Neither learning nor retention is significantly improved by giving KR to an accuracy greater than on a three-point scale.

Although these results seems to pose a problem for the information-processing view, in fact they give an important clue to the learning mechanism. I argued (Annett, 1969) that KR in positioning tasks is used in much the same way as an artilleryman uses ranging shots to locate a target. If the first attempt is an overshoot, the second attempt is shortened by an arbitrary amount; if this turns out to be an undershoot, a third shot halving the difference between the two preceding shots will be very close.

Figure 2.6 shows this strategy in the form of a simple algorithm. The interesting point here is that it is perfectly possible to learn an accurate response using a short-term memory which contains only the preceding item. The efficiency of learning depends primarily on the ability to distinguish differences in intrinsic feedback between the current response and the

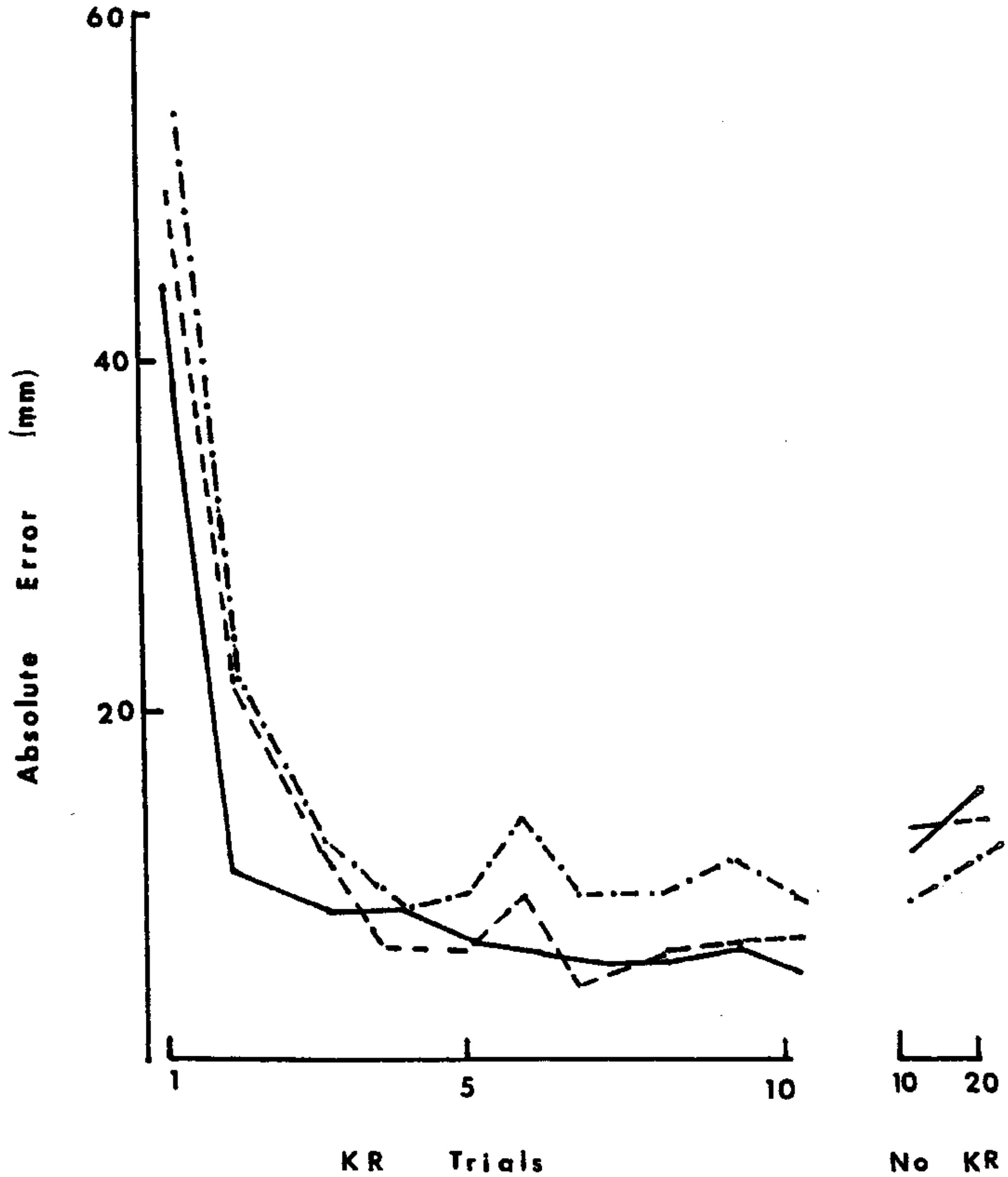

Figure 2.5. Acquiring a positioning skill under three levels of precision of KR: (—) accuracy to the nearest 2 millimetres; (---) accuracy to the nearest 17 millimetres; (-·-·-) accuracy to the nearest 40 millimetres. The three groups do not differ significantly over the 10 learning trials, but during 20 retention trials with no KR the least accurate KR gives slightly better retention.

immediately preceding response. In tasks of this kind three or four trials provide enough feedback information to enable the subject to produce responses which are as accurate as this discrimination permits. The data from Annett (1959) in Figure 2.5 suggest there is no further improvement in accuracy after four trials. Although subjects given the least accurate results (to the nearest 40mm for a target of 60mm) managed to achieve an accuracy of

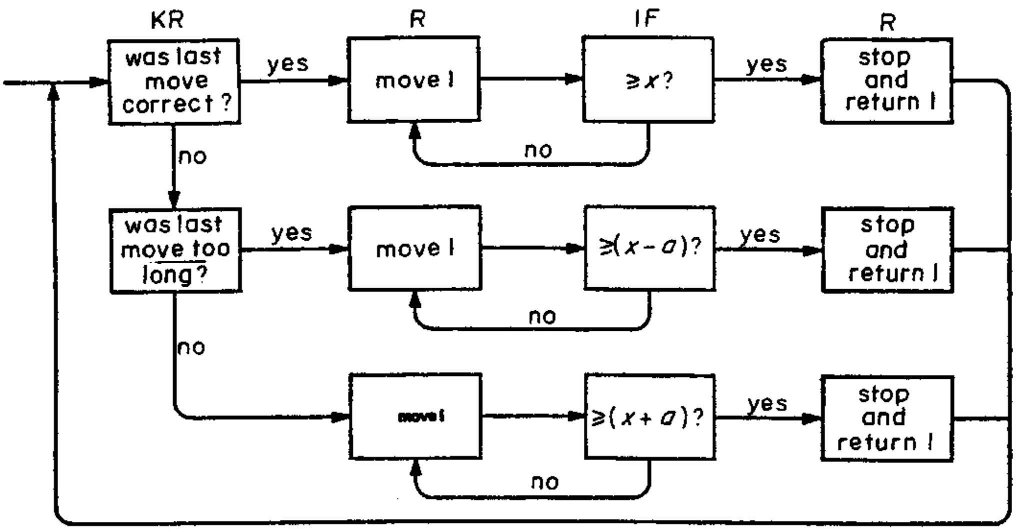

Figure 2.6. Algorithm for acquiring a positioning skill with directional KR. Depending on whether KR for the immediately preceding movement was 'correct', 'too long' or 'too short', the learner attempts to match the internal feedback from the next movement with the memory trace of the preceding movement, or to a value discernibly smaller (if KR was 'too long') or greater (if KR was 'too short'). KR = Knowledge of results; R = response; IF = internal feedback; x = memory trace of feedback from preceding movement; a = an arbitrary value of feedback stimulation in excess of the difference threshold.

around 10mm, those given KR to the nearest 17mm and 2mm did not differ. Retention is slightly better for the group given least precise KR for up to 70 post-KR trials. This may reflect the fact that providing more information than the learner can handle induces 'hunting' behaviour which could itself interfere with long-term storage.

This view of KR as providing corrective information, or guidance, requires only that the learner retain a trace of the intrinsic feedback from a response for as long as it takes to compare it with feedback from the next attempt. Two later, and better known, theories give KR a role in establishing long-term memories.

Adams's *closed loop* theory (Adams, 1971) proposed two long-term 'traces', one a *perceptual trace* which is a store of response-produced intrinsic feedback which is laid down and added to on every trial, and a second called (rather confusingly) the *memory trace* which is a brief motor programme required to initiate a response. Responses later come under the control of the perceptual trace as concurrent feedback is compared with the stored information from previous responses. In a pair of studies, Adams and his colleagues demonstrated that: (a) learning was primarily due to the strengthening of the perceptual trace since providing enhanced feedback cues leads to better learning (Adams, Goetz and Marshall, 1972); and (b) the greater the number of practice trials, the better subjects were able to estimate the correctness of their responses (Adams, Gopher and Lintern, 1977).

Schmidt (1975) produced a variant of the information-processing account of KR as *schema theory*. A schema, as understood by Schmidt, is a kind of generalised memory used in the generation of new responses of a given class. The schema notion has the advantage that it allows for the fact that skilled responses are by no means uniform, but instead are often matched to the varying needs of the occasion. The schema notion reflects the flexibility of many motor skills that enables the performer to meet new environmental demands by producing novel responses. Like Adams's theory two kinds of memory are hypothesised, one motor—the *recall schema*—and one perceptual—the *recognition schema*. The recall schema is a record of the relationships between previously executed response instructions (or motor output) under different initial conditions and their outcomes. The recognition schema stores relationships between past sensory consequences and actual outcomes or results. Both kinds of schema are built up by experience and the greater the variety of experience (within a given class of responses such as linear displacements or the hand), the easier it will be to abstract a general rule from specific cases. Schema theory therefore makes the specific prediction that variability of instances in learning will enhance transfer to new responses of the same class, and this turns out to be generally the case (Shapiro and Schmidt, 1982).

It is important to place these theories and experiments dealing with very simple responses in perspective. The provision of KR for multidimensional tasks, such as gymnastic or flying skills, is rarely a matter of giving precise quantitative information concerning a single response parameter. While overall achievement may be reduced to a single score, this may not be useful if it does not enable the learner to identify specific aspects of performance which should be modified. For example, studies of feedback, which gives information about spatial and temporal aspects of performance, do not always give better learning than simpler forms of KR (Newell and Walter, 1981). Moreover the use of video recordings, which provide detailed feedback on complex performance, has had rather mixed success as an aid to training (Rothstein and Arnold, 1976). KR is useful as an aid to learning only to the extent that the learner can identify the relationship between response output, intrinsic sensory feedback, and the outcome.

Automatisation

The development of skill is also characterised in the Fitts sequence as a progressive change in the way in which task information is processed, or more precisely in the nature of the control processes involved, such that early in skill acquisition responses are produced under direct conscious control while after a great deal of practice performance becomes automatic, being run off with little conscious attention or mental effort. Again it is tempting to adopt as a general hypothesis that most, if not all, of what we mean by skill acquisition is the process by which controlled processing becomes automatised. Logan (1985) has, however, drawn attention to a number of important differences between skilled performance and automatic behaviour. Highly skilled performance can still be very flexible; thus, skilled typists may make errors but typically correct them very quickly (Rabbitt, 1978). While a skill may include automatic procedures it often also includes a high level of cognitive activity and even metacognitive processes. Much has been made of the difficulty some skilled performers find in explaining just how they achieve their results (Annett, 1985, 1986; Berry and Broadbent, 1984) but it would be wrong to assume that this ability was present at some earlier stage of practice and then has somehow been lost along the way towards high levels of skill. Neither novices nor skilled swimmers are very good at answering certain kinds of factual questions about swimming technique (Annett, 1985), nor is it true that early attempts at a skill are dominated by conscious, controlled processes, with every move being thought out in detail. On the contrary novice swimmers and cyclists may have problems learning to control their automatic, but inappropriate, responses to the novel situation in which they find themselves.

Controlled versus automatic processing

The supposed process of automatisation has had to carry a heavy theoretical burden, but the nature of the process is still poorly understood. In the first place, the criteria for automatisation are debatable but are often said to include speed (i.e. being faster than controlled processes), relative uniformity of kinematic pattern, being involuntary, being relatively unavailable to introspective analysis, being free from interference by other concurrent tasks, and being independent of load as measured by stimulus or response information. Debates such as that between Neisser, Hirst and Spelke (1981) and Lucas and Bub (1981), or between Cheng (1985) and Schneider and Shiffrin (1985) have typically hinged on which criteria are taken as indicating true automaticity.

The nature of automatisation has been formulated in a number of different ways. Schneider and Shiffrin (1977) propose flatly that there are two kinds of process, controlled and automatic, and have sought to distinguish them in a series of studies using visual search tasks in which subjects are required to distinguish target items, for example digits, from distractors, say letters. Consistent mapping of members of the target set to a particular response produces automaticity, as measured by several of the criteria mentioned above, with quite modest amounts of practice. Automaticity in this context simply implies that there is a simple computational link between input and output, a kind of private line which is always open and not subject to crosstalk. A different and more traditional account of automaticity distinguishes between *closed-loop* and *open-loop* control. In a closed-loop task, such as compensatory tracking, the motor output is linked to and driven by an error feedback signal while in an open-loop task, such as striking a ball with a bat, the motor output is driven by a once-for-all pattern of signals, or *motor program*, which determines the form and magnitude of the response. Closed-loop tasks usually take longer to perform than open-loop tasks because feedback information is typically subject to a temporal lag and also requires processing capacity. Speed can be traded for accuracy by paying more attention to feedback information and vice versa. The effect of practice may be to make feedback information redundant (Annett and Kay 1957) or to create an accurate motor program (Keele, 1968) capable of generating responses without the need for feedback.

Motor programs

One of the major theoretical issues in motor control during the 1970s concerned the nature of motor programs. The concept of a motor program as a precise set of output instructions is not credible in the light of the considerable flexibility shown by skilled performers in adapting responses to detailed variations in task requirements. Yet there is evidence for various degrees of motor preparation in well-practised tasks of short duration. Keele and Posner (1968), for example, found probe reaction times predictably slower when probe signals are in competition with program preparation, and Rosenbaum (1985) similarly found time to initiate a response increases proportionately to the complexity of the program required to generate the response. The motor program concept became something of a straw man for those who, like Turvey (1977) argued that motor control is a highly distributed rather than a centralised process and hence requires less 'central' storage of information than the motor program theory seems to demand. This leads to an alternative conceptualisation of automaticity in terms of levels of control. Complex tasks, like driving, cannot be adequately described as either a collection of motor programs or simple feedback loops, but are better characterised as hierarchically organised control structures. At the highest level of control, strategic decisions are made about which route to follow and whether to minimise journey time or the risk of accident. At a lower level of control, specific decisions are made about whether to turn off at the next junction, whether to overtake, and so on. At a still lower level, decisions (largely unconscious) are made about how far and when to turn the steering wheel, and how hard and when to step on the brake pedal. The development of automaticity in this view refers to the gradual changes in the focus of attention and control away from the lower functions towards higher level goals.

Fuchs (1962) demonstrated this principle in the context of a second-order tracking task. In zero order, the subject responds to the current size of the

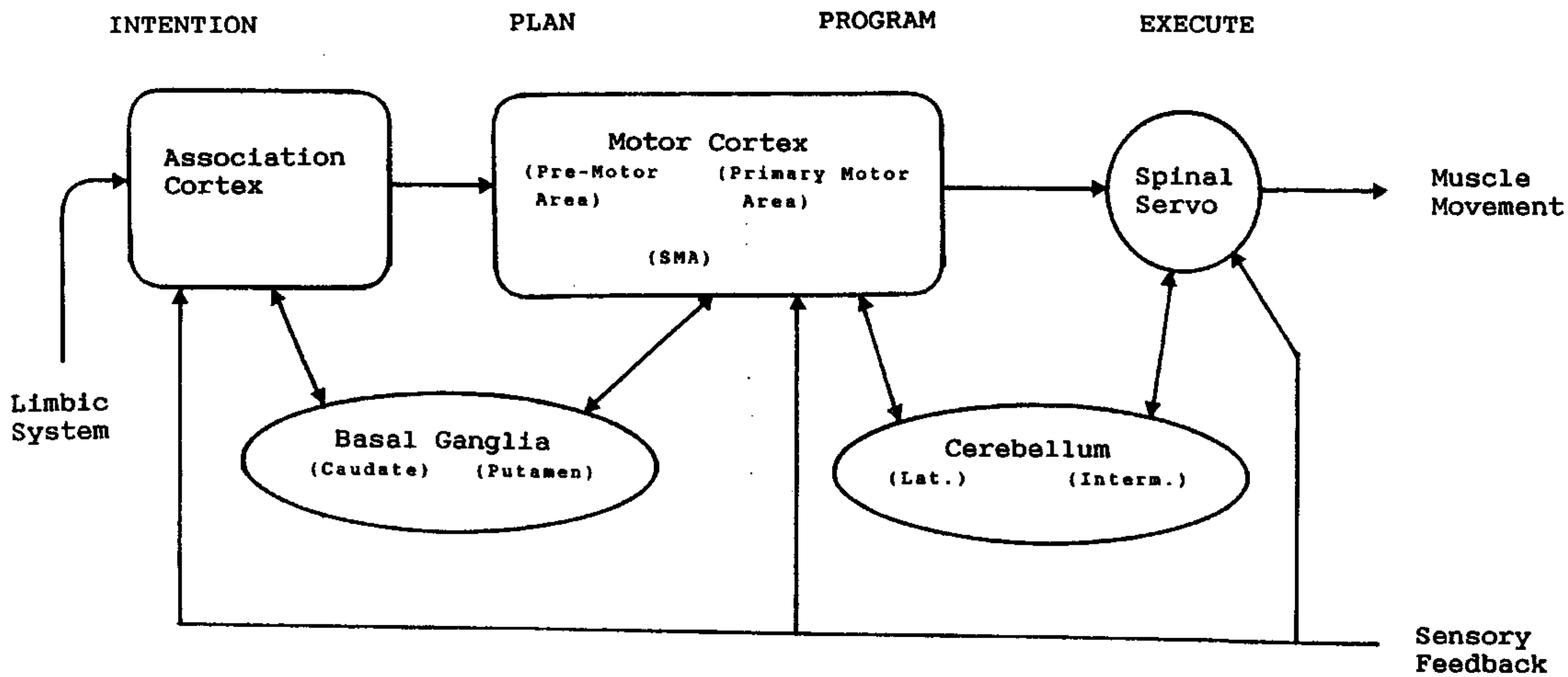

Figure 2.7. A simplified diagram of the principal structures involved in the production of a voluntary action.

error signal; in first-order control, the subject responds to the rate at which the error signal is changing; and in second-order control, to the acceleration of the error. The performance of a human tracker can be described approximately by a differential equation with the coefficients in the successive terms of the equation taken as estimates of the weights given by the subject to position, velocity, and acceleration information. With nine two-minute trials daily for 20 days, the weight given by subjects to the momentary position error decreased while the weighting given to acceleration error steadily increased. After 20 days, when subjects were required to carry out a second tracking task simultaneously, this change was reversed and performance tended to regress back from acceleration control to position control. Some clear examples of changes in level of control can be found in keyboard skills. Shaffer (1981), in an elegant analysis of the performances of highly skilled pianists using a specially equipped piano, has shown how the relative timing of notes is subject to high level control. Variations in timing, or rubato, are important to the emotional expression of music. A detailed analysis over different performances showed that the relative timing of individual keystrokes was consistent with varying the rate of an internal 'clock' rather than piecemeal adjustments to individual inter-keystroke intervals. The motor programs representing sequences of movements were themselves subject to a timebase that the virtuoso varies to express his or her musical intentions. The simulation of typing skill by Rumelhart and Norman (1982) described near the beginning of this chapter also illustrates this principle of different levels of control. The model envisages at least two distinct levels: a higher level concerned with interpreting the 'copy' to be typed and getting the words (word schemata) and letters (keypress schemata) in the right sequence; and a lower level which is concerned with moving the fingers around to locate particular keys. The common error of doubling the wrong letter for instance typing 'bokk' instead of 'book', can be interpreted as implying an intermediate level of control representing double striking—a doubling schema—which, from time to time, is applied to the wrong letter. The theory that automatisation refers to the lowest levels of control is consistent with current theories of motor control that strongly suggest, on both behavioural and neurological grounds, that voluntary action involves the integration of a number of semi-autonomous systems, rather like an army in which subordinates have quite a lot of freedom to interpret, sometimes even reject, orders from above on the basis of their special knowledge of local conditions.

NEURAL BASES OF MOTOR LEARNING

The viewpoint adopted in this chapter is that skill acquisition is likely to involve more than one learning process. Recent evidence on the neural bases of motor learning supports this general position and adds an important dimension to the purely behavioural studies reviewed in preceding sections. Figure 2.7 summarises current views on the principal neural structures involved in the production of voluntary movement and their interconnections. At least three different 'levels' of the nervous system are distinguishable: the top level which is concerned with strategy or *what* to do; the middle level is concerned with tactics or *how* to do it; and the third level which controls the actual execution. The effects of training and practice may operate at any or all of these levels and the specific nature of the learning mechanism will depend in part on which structures are involved.

At the lowest level, the motor servo controls the coactivation of muscles which is necessary for smooth changes in the angles made by the joints to take place. There are two principal feedback circuits, one via the spinal cord and one at a high level via the cerebellum. The latter is particularly important in relating muscular output to concurrent data from internal and external senses. It is this circuit which is modified when adapting to new perceptual–motor relationships, for example when adjusting to spectacles which invert the visual field or to tracing a pattern seen in a mirror. 'Getting your sea-legs' is another example of the adaptation of the motor output to match the unusual relationships between the vestibular sensations of movement and the normal visual cues. This kind of motor learning is a temporary readjustment: the sailor ashore quickly loses his sea-legs. Marr (1969) has suggested a specific mechanism for this kind of adaptation involving an interaction between the *inferior olive* and the *cerebellar cortex*. Motor output signals are copied to the inferior olive which then receives feedback from the receptors; a comparison between the intended and the actual output is then signalled back to the cerebellar cortex and a mismatch results in a modification of the response of specific groups of cells to incoming information. Marr's theory has been confirmed by Ito (1984) who also showed that the effect was produced by a temporary change in the responsiveness of Purkinje cells to a specific neurotransmitter. This kind of learning, or adaptation as Brooks (1986) prefers to call it, can proceed independently of the higher centres of motor control and is unaffected by lesions which affect other kinds of memory, while damage to the inferior olive prevents learning at this level and destroys the effects of previous adaptation.

Another part of the cerebellum, the lateral cerebellum, is concerned with a different kind of learning at the middle level of the motor control hierarchy. In a series of experiments in which monkeys were trained to make simple positioning responses, Brooks (Brooks, 1986; Brooks, Kennedy and Ross, 1983) noted that learning occurred in two distinct phases. In the first the monkeys did not know which was the correct response, a right or left movement, and their 'uncertainty' was demonstrated in long reaction times and slow controlled movements of the lever. However, once the animals had discovered in which direction to move the lever, and began to do so on a better than chance basis, the pattern of their motor responses also began to change. Slow, somewhat irregular, controlled adjustment began to give way to fast and accurate biphasic movements characterised by an initial acceleration matched to the required movement amplitude, followed by a precisely timed deceleration—in short a typical motor program. This type of motor learning involves interaction between the cerebellum and two frontal areas of the brain, the *pre-motor area* (PMA) and the *supplementary motor area* (SMA). A comparator system in which the actual motor output is matched to an intended output is required. Brooks (1988) noted that both the PMA and SMA are connected with the *cingulate gyrus*, part of the *limbic system* which mediates needs and wants. Once the organism has decided *what* it wants to achieve it then becomes possible to match intentions with achievements, that is to learn *how*.

While interactions between association cortex and the limbic system represent the highest level of control, what the organism wants or intends, the SMA and the PMA are involved in anticipatory planning of action. Using a brain scanning technique to measure the flow of blood in different parts of the brain as an indication of local neural activity, Roland *et al.* (1980) investigated SMA activity during successive stages of learning a sequential manual skill. Subjects were required to learn a series of simple movements, touching the tip of the thumb with the fingertips of the same hand in a prescribed sequence. In this task, localised blood flow indicated neural activity in both the *primary motor cortex* and the SMA. When subjects were asked to carry out the task in imagination only, the bloodflow to the primary motor cortex was reduced but remained high in the SMA. By contrast when subjects were required to squeeze rhythmically a small spring-loaded cylinder between finger and thumb, an overlearned and rather boring task, SMA activity was reduced while primary motor cortex activity remained high. These results are consistent with the hypothesis that these areas of the frontal cortex are brought into play during the learning of a motor task but are not needed for the routine execution of a well-learned activity. Passingham (1987) showed that removal of the SMA abolishes the ability to learn movements cued by preceding actions in sequential tasks. Sasaki and Gemba (1986) were able temporarily to abolish a learned wrist movement in monkeys by cooling the surface of the PMA, but in this case the skill returned after restoration of normal temperature showing that this area is mediating a longer term motor memory. Brooks (1988) concludes that these cortical areas are modulated by the limbic system during motor learning and help to establish both short- and long-term motor memories relating motor actions to the demands of external and internal stimuli.

One of the striking features of motor learning is its persistence. Skills such as bicycle riding and swimming are not forgotten even after years without practice. Even the relatively 'cognitive' skill of typing is resistant to lack of practice as shown in a study by Hill (1934, 1957) who learned to type first in 1907 and, with no intervening practice, relearned after 25 years and again 50 years after the original learning. In the first relearning trial, it took only one day's practice to regain the typing speed it had originally taken 27 days to achieve. On the second relearning trial, he regained the original end of training performance level after only 8 days' practice, clear evidence of long-term retention of the skill. Milner's famous amnesic patient H. M. was able to learn and retain motor skills, such as tracking and mirror drawing while having no memory of the tester or previous training sessions (Corkin, 1968). H. M. had suffered lesions to the *hippocampus* and *amygdala*, two areas which have been shown in animal studies (Mishkin, Malamut and Bachevalier, 1984) to be responsible for learning to recognise objects and their locations; however, these animals can learn, albeit somewhat slowly, to connect visual stimuli with particular responses. The *striatum*, an evolutionary ancient part of the forebrain, has connections with both sensory and motor systems. Animals with lesions in this area fail to learn simple perceptual–motor habits. While the neurological evidence is still far from complete, it seems that there are a number of different neural mechanisms underlying the acquisition of skill, some serving the cognitive aspects of skill and others operating at more primitive levels in the formation of perceptual–motor links and the selection of efficient motor patterns.

SUMMARY AND CONCLUSIONS

A skill is a solution to a problem and the view is taken that skill acquisition is best understood if the nature of the problem to be solved is first understood. Information-processing concepts provide the best available framework within which to analyse specific skills. Two contrasting examples, bicycle riding and typing, illustrate how proficiency is acquired. Analysis is particularly important in designing training since it enables the instructor/trainer to design procedures to help the learner solve the specific skill problem.

The acquisition of skill is marked by qualitative and quantitative changes in performance, both of which may provide clues to underlying learning processes. The log–log linear law of learning, which describes the typical relationship between performance time and number of practice trials, has often been interpreted as indicating a single underlying learning process. However, qualitative changes in performance may suggest a number of different sources of improvement, including a changed understanding of the task, selection of different responses, variations in technique, and the redistribution of attention.

Skill is acquired both through the automatic effects of repetitive practice, and also through various methods of instruction which involve high level cognitive processes. The relationship between cognitive and non-cognitive processes in skill is still not fully understood but must depend on links between stored representations of actions (procedural knowledge), and linguistic units (declarative knowledge). Observational learning is mediated by action–perception processes, and hence effective demonstrations must take into account the way the trainee perceives and interprets complex action patterns. Verbal communication about actions is often effective only if it can make use of established action imagery. Trainees find it easier to follow instructions which summon up clear movement images.

Practice offers the opportunity to acquire information relevant to the performance of a skill. This may include information about patterns of stimuli presented by the task, and about the consequences of different responses. Some theorists have emphasised the perceptual aspects of skill learning while classical learning theory has emphasised the selective effects of consequences, especially in the form of knowledge of results. KR has to be placed in the context of all the information available to the skilled performer, especially other forms of feedback information which are intrinsic to the task. The principal role of KR seems to be informative rather than reinforcing in the sense used by behaviourists. In the early stages of learning, KR may be used to identify the essential parameters of a response pattern, especially if they are difficult to ascertain by other means. The fact that mental practice has been shown to have some effect on skill acquisition does, however, suggest that not all the effects of practice can be attributed to information feedback, and there is clearly a role for sheer repetition as such in acquiring skill.

Repetition generally leads to automatisation, but this does not always mean that performance is inaccessible to cognitive influence. A better description is that attention is directed to more abstract features of performance, such as the sequence of actions, or their timing and rhythm. Neurological evidence tends to confirm the existence of several different motor learning processes, some controlled by parts of the brain responsible for organisation and planning, and others by mechanisms which relate actions to intentions.

REFERENCES

Adams, J. A. (1957). The relationship between certain measures of ability and the acquisition of a psychomotor criterion response, *Journal of General Psychology*, **56** 121–134.

Adams, J. A. (1971). A closed loop theory of motor learning, *Journal of Motor Behaviour*, **3**, 111–150.

Adams, J. A. (1987). Historical review and appraisal of research on the learning, retention and transfer of human motor skills. *Psychological Bulletin*, **101**, 41–74.

Adams J. A. Goetz, E. T. and Marshall, P. H. (1972). Response feedback and motor learning, *Journal of Experimental Psychology,* **92**, 391–397.

Adams, J. A., Gopher, D. and Lintern, G. (1977). Effects of visual and proprioceptive feedback on motor learning, *Journal of Motor Behaviour,* **9**, 11–22.

Anderson, J. R. (1982). The acquisition of cognitive skill, *Psychological Review,* **89**, 369–406.

Anderson, J. R. (1987). Skill acquisition: Compilation of weak-method problem solutions, *Psychological Review,* **94**, 192–210.

Annett, J. (1959). *Aspects of the Acquisition of Skill.* Unpublished D Phil thesis, University of Oxford.

Annett, J. (1969). *Feedback and Human Behaviour.* Harmondsworth: Penguin.

Annett, J. (1982). Action, language and imagination. In L. Wankel and R. B. Wilberg (eds). *Psychology of Sport and Motor Behavior: Research and Practice*, pp. 271–282. Edmonton: University of Alberta.

Annett, J. (1985). Motor learning: A review. In H. Heuer, U. Kleinbeck and K-H. Schmidt (eds). *Motor Behavior: Programming, Control and Acquisition,* pp. 189–212. Berllin: Springer.

Annett, J. (1986). On knowing how to do things. In H. Heuer and C. Fromm (eds). *Generation and Modulation of Action Patterns,* pp. 187–200. Berliln: Springer.

Annett, J. (1988). Motor learning and retention. In M. M. Gruneberg, P. E. Morris and R. N. Sykes (eds). *Practical Aspects of Memory: Current Research and Issues,* Vol. 2, pp. 434–440. London: Academic Press.

Annett, J. (1990). Relations between verbal and gestural explanations. In G. R. Hammond (ed). *Cerebral Control of Speech and Limb Movements*, pp. 295–314. Amsterdam: North Holland.

Annett, J. and Duncan, K. D. (1967). Task analysis and training design, *Occupational Psychology,* **41**, 211–221.

Annett, J. and Kay, H. (1956). Skilled performance, *Occupational Psychology,* **30**, 112–117.

Annett, J. and Kay, H. (1957). Knowledge of results and skilled performance, *Occupational Psychology,* **31** 69–79.

Annett, J., Duncan, K. D., Stammers, R. B. and Gray, M. J. (1971). *Task Analysis.* London: HMSO.

Argyle, M. (1969). *Social Interaction.* London: Methuen.

Bainbridge, L. (1979). Verbal reports as evidence of the process operator's knowledge, *International Journal of Man–Machine Studies,* **11**, 311–436.

Bainbridge, L. (1988). Types of representation. In L. P. Goodstein, H. B. Andersen and S. E. Olsen (eds). *Tasks, Errors and Mental Models,* pp. 55–91. London: Taylor and Francis.

Bandura, A. (1977). *Social Learning Theory.* Englewood Cliffs, NJ: Prentice-Hall.

Bandura, A. (1986). *Social Foundations of Thought and Action: A social cognitive theory.* Englewood Cliffs NJ: Prentice-Hall.

Bartlett, F. C. (1958). *Thinking: An experimental and social study.* London: Allen and Unwin.

Bernstein, N. (1967). *The Co-ordination and Regulation of Movements.* London: Pergamon Press.

Berry, D. C. and Broadbent, D. E. (1984). On the relationship between task performance and associated verbal knowledge, *Quarterly Journal of Experimental Psychology,* **36A**, 209–231.

Berry, D. C. and Broadbent, D. E. (1984). On the relationship between task performance and associated verbal knowledge *Quarterly Journal of Experimental Psychology,* **36A**, 209–231.

Berry, D. C. and Broadbent, D. E. (1987). Explanation and verbalisation in a computer-assisted search task, *Quarterly Journal of Experimental Psychology,* **39A**, 585–609.

Berry, D. C. and Broadbent, D. E. (1988). Interactive tasks and the implicit-explicit distinction, *British Journal of Psychology,* **79**, 251–272.

Bilodeau, E. A. (1953). Speed of acquiring a simple motor response as a function of the systematic transformation of KR, *American Journal of Psychology,* **60**, 409–420.

Bilodeau, E. A. and Bilodeau, I. McD. (1958a). Variation in temporal intervals among critical events in five studies of knowledge of results, *Journal of Experimental Psychology,* **55**, 603–612.

Bilodeau, E. A. and Bilodeau, I. McD. (1958b). Variable frequency of knowledge of results and the learning of a simple skill, *Journal of Experimental Psychology,* **55**, 379–383.

Bilodeau, E. A. and Rosenbach, J. H. (1953). Acquisition of response proficiency as a function of rounding error in informative feedback, *USAF Human Resource Research Center Research Bulletin,* No. 53–21.

Bilodeau, I. McD. (1969). Information feedback. In E. A. Bilodeau and I. McD. Bilodeau (eds). *Principles of Skill Acquisition.* New York: Academic Press.

Book, W. F. (1908). The psychology of skill: With special reference to its acquisition in typewriting, *University of Montana Publications in Psychology, Bulletin No. 53.*

Brooks, V. B. (1986). *The Neural Basis of Motor Control.* Oxford: Oxford University Press.

Brooks, V. B. (1988). Limbic assistance in task-related use of motor skill. *Paper presented to the Study Week on the Principles of Design and Operation of the Brain. Pontificia Academia Scientarium, the Vatican.*

Brooks, V. B., Kennedy, P. R. and Ross, H. G. (1983). Movement programming depends on understanding of behavioural requirements, *Physiology and Behavior,* **31**, 561–563.

Bryan, W. L. and Harter, N. (1897). Studies in the physiology and psychology of the telegraphic language, *Psychological Review,* **4**, 27–53.

Bryan, W. L. and Harter, N. (1899). Studies on the telegraphic language: The acquisition of a hierarchy of habits, *Psychological Review,* **6**, 345–375.

Burwitz, L. (1981). The use of demonstrations and video-tape recorders in sport and physical education. In I. M. Cockerill and W. W. MacGillivary (eds). *Vision and Sport.* Cheltenham: Stanley Thornes.

Chase, W. G. and Simon, H. A. (1973). Perception in chess, *Cognitive Psychology,* **4**, 55–81.

Cheng, P. W. (1985). Restructuring vs automaticity: Alternative accounts of skill acquisition, *Psychological Review,* **92**, 414–423.

Corbin, C. B. (1972). Mental practice. In W. D. Morgan (ed.). *Ergogenic Aid and Muscular Performance.* New York: Academic Press.

Corkin, S. (1968). Acquisition of motor skill after bilateral medial temporal lobe excision, *Neuropsychologia,* **6**, 255–265.

Crossman, E. R. F. W. (1959). A theory of the acquisition of speed skill, *Ergonomics,* **2**, 153–166.

Cutting, J. E. (1978). Generation of male and female synthetic walkers, *Perception,* **1**, 395–405.

de Groot, A. D. (1965). *Thought and Choice in Chess.* The Hague: Mouton.

Doyle, A. J. R. (1988). The essential human contribution to bicycle riding. In J. Patrick and K. D. Duncan (eds). *Training, Human Decision Making and Control.* Amsterdam: North Holland.

Ebbinghaus, H. (1885). *Uber das Gedachtnis.* Leipzig: Duncker. (Published [1964] in translation as *Memory: A contribution to experimental psychology.* New York: Dover.)

Feltz, D. L. and Landers, D. M. (1983). The effects of mental practice on motor skill learning and performance: A meta-analysis, *Journal of Sport Psychology,* **5**, 25–57.

Feltz, D. L., Landers, D. M. and Becker, B. J. (1988). A revised meta-analysis of the mental practice literature on motor skill learning. *Background paper prepared for the Committee on Techniques for the Enhancement of Human Performance, National Academy of Sciences.* (Available through the publication on request program.)

Ferster, C. B. and Skinner, B. F. (1957). *Schedules of Reinforcement.* New York: Appleton-Century-Crofts.

Fitts, P. M. (1964). Perceptual-motor skill learning. In A. W. Melton (ed.) *Categories of Human Learning.* New York: Academic Press.

Fitts, P. M. and Posner, M. I. (1967) *Human Performance* Belmont, C. A. Brookes/Cole Publishing Company.

Fleishman, E. A. (1960). Abilities at different stages of practice in rotary pursuit, *Journal of Experimental Psychology,* **60**, 162–171.

Fleishman, E. A. and Hempel, W. E. (1954). Changes in factor structure of a complex psychomotor task as a function of practice, *Psychometrika,* **19**, 239–252.

French, K. E. and Thomas, J. R. (1987). The relation of knowledge development to children's basketball performance, *Journal of Sport Psychology,* **9**, 15–32.

Fuchs, A. H. (1962). The progression–regression hypothesis in perceptual–motor skill learning. *Journal of Experimental Psychology,* **63** 177–183.

Geschwind, N. and Kaplan, E. (1962). A human disconnection syndrome, *Neurology,* **12**, 675–685.

Green, R. F., Zimilies, H. L. and Spragg, S. D. S. (1955). The effects of varying degrees of knowledge of results on knob-setting performance, *SPECDEVCEN Technical Report 241–76–20.*

Hill, L. B. (1934). A quarter century of delayed recall, *Journal of General Psychology,* **44**, 231–238.

Hill, L. B. (1957). A second quarter century of delayed recall, or relearning at eighty, *Journal of Educational Psychology,* **48**, 65–69.

Ho, L. and Shea, J. B. (1978). Effects of relative frequency of knowledge of results on retention of a motor skill, *Perceptual and Motor Skills,* **46**, 859–866.

Houston, R. C. (1947). *The Function of Knowledge of Results in Learning a Complex Motor Skill.* Unpublished MA thesis, Northwestern University, Evanston, Illinois.

Hull, C. L. (1943). *Principles of Behavior.* New York: Appleton-Century-Crofts.

Imwold, C. H. and Hoffman, S. J. (1983). Visual recognition of a gymnastic skill by experienced and inexperienced inexperienced instructors. *Research Quarterly for Exercise and Sport Sciences,* **54**, 149–155.

Ito, M. (1984). *The Cerebellum and Neural Control.* New York: Raven Press.

Jacobson, E. (1932). Electrophysiology of mental activities, *American Journal of Psychology,* **44**, 677–694.

James, W. (1890). *Principles of Psychology.* New York: Henry Holt.

Johansson, G. (1973), Visual perception of biological motion and a model for its analysis, *Perception and Psychophysics*, **14** 201–211.

Johnson, P. (1982). The functional equivalence of imagery and movement, *Quarterly Journal of Experimental Psychology,* **34A**, 349–365.

Jones, M. B. (1970). A two process theory of inidividual differences in motor learning, *Psychological Review*, **77**, 353–360.

Judd, C. H. (1908). The relation of special training and intelligence, *Educational Review*, **36**, 28–42.

Kawai, M. (1965). Newly acquired precultural behavior in the natural troupe of Japanese monkeys on Koshima islet, *Primates*, **6**, 1–30.

Keele, S. W. (1968). Movement control in skilled motor performance, *Psychological Bulletin*, **70**, 387–403.

Keele, S. W. and Posner, M. I. (1968). Processing of visual feedback in rapid movements, *Journal of Experimental Psychology*, **77** 155–158.

Logan, G. D. (1985). Skill and automaticity: Relations, implications and future directions. *Canadian Journal of Psychology*, **39**, 367–386.

Long, J. B. (1975). Effects of randomly delayed visual and auditory feedback on keying performance, *Ergonomics*, **18**, 337–347.

Long, J. B. (1976). Visual feedback and skilled keying: Differential effects of masking the print copy and the keyboard, *Ergonomics*, **19** 93–110.

Long, J. B., Nimmo-Smith, I. and Whitfield, A. (1983). In W. E. Cooper (ed.). *Cognitive Aspects of Skilled Typewriting*, pp. 145–195. New York: Springer.

Large, I. and Thorndike, E. L. (1935). The influence of delay in the after-effect of a connection, *Journal of Experimental Psychology*, **18**, 186–194.

Lucas, M. and Bub, D. (1981). Can practice result in the ability to divide attention between two complex language tasks? Comment on Hirst *et al. Journal of Experimental Psychology: General*, **110**, 495–498.

Mackworth, N. (1950). Researches in the measurement of human performance. *Medical Research Council Special Report Series No. 268.* London: HMSO. (Reprinted in W. H. Sinaiko, (ed.) (1961) *Selected Papers on Human Factors in the Design and Use of Control Systems.* New York: Dover.

MacKay, D. G. (1981). The problem of rehearsal or mental practice. *Journal of Motor Behavior*, **13**, 274–285.

MacKay, D. G. (1982). The problems of flexibility, fluency and speed-accuracy tradeoff in skilled behavior, *Psychological Review*, **89**, 483–506.

Marr, D. (1969). A theory of cerebellar cortex, *Journal of Physiology*, **141**, 437–470.

McLeod, P. (1977). A dual task response modality effect: Support for multi-process models of attention, *Quarterly Journal of Experimental Psychology*, **29**, 651–667.

Meltzoff, A. N. and Moore, M. K. (1977). Imitation of facial and manual gestures, *Science*, **198**, 75–80.

Miller, G. A. (1956). The magical number seven, plus or minus two: Some limits on our capacity for processing information, *Psychological Review*, **63**, 81–97.

Miller, G. A., Galanter, E. and Pribram, K. (1960). *Plans and the Structure of Behavior:* New York: Holt, Reinhart & Winston.

Miller, R. B. (1953). Handbook of training and equipment design, *USAF WADC Technical Report 53-136.*

Mishkin, M., Malamut, B. and Bachevalier, J. (1984). Memories and habits: Two neural systems. In G. Lynch, J. L. McGough and N. M. Weinberger (eds). *Neurobiology of Learning and Memory*. New York: Guilford Press.

Morin, R. E. and Gagné, R. M. (1951). Pedestal sight manipulation test performance as influenced by variations in type and amount of psychological feedback, *USAF HRRC Research Note P & MS 51-7.* Brooks AFB, TX: US Air Force Human Resources Research Command.

Neisser, U., Hirst, W. and Spelke, E. S. (1981). Limited capacity theories and the notion of automaticity: Reply to Lucas and Bub, *Journal of Experimental Psychology: General,* **110**, 499–500.
Newell, A. and Rosenbloom, P. S. (1981). Mechanisms of skill acquisition and the law of practice. In J. R. Anderson (ed). *Cognitive Skills and their Acquisition*. Hillsdale, NJ: Lawrence Erlbaum.
Newell, K. M. and Walter, C. B. (1981). Kinematic and kinetic parameters as information feedback in motor skill acquisition, *Journal of Human Movement Studies,* **7**, 235–254.
Newtson, D. (1980). Foundations of attribution: The perception of ongoing behavior. In J. Harvey, W. Ickes and R. Kidd (eds). *New Directions in Attribution Research*. Hillsdale NJ: Lawrence Erlbaum.
Passingham, R. E. (1987). Two cortical systems for directing movements. In *Motor Areas of the Cerebral Cortex: Ciba Foundation Symposium 132*, pp. 151–164. Chichester: Wiley.
Rabbitt, P. M. A. (1978). Detection of errors by skilled typists, *Ergonomics,* **21**, 945–958.
Richardson, A. (1967). Mental practice: A review and discussion. *Research Quarterly for Exercise and Sport Sciences,* **38**, 95–107 and 263–273.
Roland, P. E., Larsen, B., Lassen, N. A. and Skinhoj, E. (1980). Supplementary motor area and other cortical areas in organisation of voluntary movements in man, *Journal of Neurophysiology,* **43**, 118–136.
Rosenbaum, D. A. (1985). Motor programming: A review and scheduling theory. In H. Heuer, U. Kleinbeck and K-H. Schmidt (eds). *Motor Behavior: Programming control and acquisition,* pp. 1–33. Berlin: Springer.
Rothstein, A. L. and Arnold, R. K. (1976). Bridging the gap: Application of research on videotape feedback and bowling, *Motor Skills: Theory into Practice,* **1**, 35–62.
Rumelhart, D. E. and Norman, D. A. (1978). Accretion, tuning and restructuring: three modes of learning. In J. W. Cotton and Roberta L. Klatzky (eds). *Semantic Factors in Cognition*, pp. 37–53.
Rumelhart, D. E. and Norman, D. A. (1982). Simulating a skilled typist: A study of skilled cognitive motor performance, *Cognitive Science,* **6**, 1–36.
Salmoni, A. W., Schmidt, R. A. and Walter, C. B. (1984). Knowledge of results and motor learning: a review and critical appraisal, *Psychological Bulletin,* **95**, 355–386.
Sasaki, K. and Gemba, H. (1986). Effects of premotor cortex cooling upon visually initiated hand movements in the monkey, *Brain Research,* **374**, 278–286.
Schmidt, R. A. (1975). A schema theory of discrete motor skill learning, *Psychological Review,* **82**, 225–260.
Schmidt, R. A., Young, D. E., Swinnen, S. and Shapiro, D. C. (1989). Summary knowledge of results for skill acquisition: Support for the guidance hypothesis, *Journal of Experimental Psychology: Learning Memory and Cognition,* **15**, 352–359.
Schneider, W. and Shiffrin, R. M. (1977). Controlled and automatic human information processing 1: Detection, search and attention, *Psychological Review,* **84** 1–66.
Schneider, W. and Shiffrin, R. (1985). Categorisation (restructuring) and automatisation: Two separable factors, *Psychological Review,* **92**, 424–428.
Scully, D. M. and Newell, K. M. N. (1985). Observational learning and the acquisition of motor skills: Towards a visual perception perspective, *Journal of Human Movement Studies,* **11**, 169–186.
Seibel, R. (1963). Discrimination reaction time for a 1023-alternative task, *Journal of Experimental Psychology,* **66**, 215–226.

Shaffer, L. H. (1981). Performances of Chopin, Bach and Bartok: Studies in motor programming, *Cognitive Psychology,* **13** 326–376.

Shapiro, D. C. and Schmidt, R. A. (1982). The schema theory: recent evidence and developmental implications. In J. A. S. Kelso and J. E. Clark (eds). *The Development of Movement Control and Coordination*, pp. 113–173. New York: Wiley.

Sheffield, F. D. (1961). Theoretical considerations in the learning of complex sequential tasks from demonstration and practice. In A. A. Lumsdaine (ed.). *Student Response in Programmed Instruction.* Washington DC: NAS-NRC.

Skinner, B. F. (1953). *Science and Human Behavior.* New York: Macmillan.

Smyth, M. M. and Pendelton, L. R. (1989). Working memory for movements, *Quarterly Journal of Experimental Psychology,* **41A**, 235–250.

Snoddy, G. S. (1926). Learning and stability, *Journal fo Applied Psychology*, **10**, 1–36.

Spelke, E., Hirst, W. and Neisser, U. (1976). Skills of divided attention, *Cognition,* **4**, 215–230.

Starkes J. L. (1987). Skill in field hockey: The nature of the cognitive advantage, *Journal of Sport Psychology,* **9**.

Suinn, R. (1972). Behavior rehearsal training for ski races, *Behavior Therapy,* **3** 210–212.

Swift, E. J. (1910). Relearning a skillful act: An experimental study of neuromuscular memory, *Psychological Bulletin,* **7** 17–19.

Thomas, J. R., French, K. E. and Humphries, C. A. (1986). Knowledge development and sport skill performance: Directions for motor behavior research, *Journal of Sport Psychology,* **8**, 259–272.

Thorndike, E. L. (1932). *The Fundamentals of Learning.* New York: Teacher's College, Columbia University.

Thorndike, E. L. (1933). A theory of the effects of the action or the after effects of a connection upon it, *Psychological Review,* **40**, 434–489.

Trowbridge, M. H. and Cason, H. (1932). An experimental study of Thorndike's theory of learning, *Journal of General Psychology,* **7**, 245–258.

Turvey, M. T. (1977). Preliminaries to a theory of action with reference to vision. In R. Shaw and J. Bransford (eds). *Perceiving Acting and Knowing: Towards an ecological psychology.* Hillsdale NJ: Lawrence Erlbaum.

Turvey, M. T. and Kugler, P. N. (1984). An ecological approach to perception and action. In H. T. A. Whiting (ed.). *Human Motor Actions: Bernstein reassessed,* pp. 373–412. Amsterdam: North Holland.

van Lawick-Goodall, J. (1971). *In the Shadow of Man.* London: Collins.

Vickers, J. N. (1988). Knowledge structures of expert–novice gymnasts, *Journal of Human Movement Science,* **7**, 47–72.

Welford, A. T. (1987). On rates of improvement with practice, *Journal of Motor Behavior,* **19**, 401–415.

Whiting, H. T. A., Bijlard, M. J. and den Brinker, B. P. L. M. (1987). The effect of the availability of a dynamic model on the acquisition of a complex cyclical action, *Quarterly Journal of Experimental Psychology,* **39A**, 43–59.

Woodrow, H. (1939). Factors in improvement with practice, *Journal of Psychology,* **7**, 55–70.