Current ideas on motor control and learning: implications for therapy.

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Introduction.

In this chapter some recent notions and trends in motor control and learning are discussed. The main focus will be on human behavior instead of on the underlying (neuro-)physiological mechanisms. The human organism is viewed as a complex self-regulating system capable of receiving, processing and transmitting information and indissolubly connected with the environment. This basic information processing notion allows us to ask a number of questions that appear relevant in the learning and re-learing of skill. Rehabilitation will for a large part be viewed as the (re-)acquisition of skills. Therefore theoretical notions on skill acquisition as they exist in cognitive experimental psychology are relevant for therapists. The chapter is not focussed on behavior in water per se but has a broader scope, it is focussed at the rehabilitation of the patient with motor disorders.

The reader should not expect clear answers to the many existing problems. In fact, there are not many (if any) answers to give. Hence, the chapter does not present you with an array of facts, immediately applicable in therapeutical situations. The main purpose of the present text is to develop a theoretical new look to many old problems.

How are movements controlled?

Each day we perform thousands of movements, almost without effort or attention. Everything looks so easy for the normal, healthy adult, but we have forgotten the trouble a young child has with "simple" motor skills such as walking, eating, holding a glass, regulating balance, reaching, climbing etc. We have forgotten the thousands of repetitions necessary for mastering these skills.

However, when observing a patient suffering from the consequences of damage to the motor system, we immediately realize the vulnerability of the system and we suddenly realize that it is only "one step" from the high skilled smooth performance of the healthy adult to the impaired invalid motor behavior of the patient.

Motor control is a complex process. Consider for example the following simple skill viz. the catching of a ball. When analyzing this task in terms of information processes it becomes clear that even such a simple task comprises a large number of processes.

Cognitive/motor processes which play a role in the skill of catching a ball.

- the instruction must be understood
- the instruction must be stored in memory for a short time (STM-function)
- attention span must be sufficient
- visual fixation of the object
- identification of the object as a ball
- adequate perception of the trajectory of the ball
- coordinated movement of head and eyes
- knowledge of body position (processing of proprioceptive and expproprioceptive information)
- selection of the adequate response
- linking of the actual response to similar responses performed in the past (LTM-function)
- retrieval of a raw, prototypical action schema from long term memory
- the adjustment of the raw action schema to the actual requirements (such as force, velocity, accuracy)
- regulation of balance
- the coordination of agonistic and antagonistic muscles
- start of the movement
- processing of feedback
- correction of the running movement on base of processed afferent feedback
- STOP
- processing of knowledge of results
- start of a new attempt.

This example clearly shows that motor control is a multi layered process. There are no ready made efferent instructions regulating the movement in a strictly "top-down" order, but the movement is constructed on basis of several streams of input.

This example has implications for the diagnosis of motor disorders, since it indicates that observed problems in the overt motor output can be understood in terms of disorders of one (or more) of the abovementioned processes (the application of such a process-oriented approach to the diagnosis of motor disorders has been described elsewhere. Hulstijn & Mulder (1986), Mulder Hulstijn & Verhulsdonck (1987).

One of the most interesting sources of sensory input is the perceptual input. Therefore in the next section the relationship between perception and action will be discussed in more detail.

Perception and action.

Traditionally the visual system has been described as an exteroceptor (as a source of extrinsic information). It was thought of as a receptor that provides information only about the movements of other objects in the environment. Although it does have this capability, it has been indicated recently that the eye can also function as a proprioceptor. These recent notions are strongly influenced by the work of Gibson (1979) who considered vision as a far richer source of information than is implied by passive registration of events in the environment. Think of the retina as being bombarded with rays of light from the objects in the visual field. The locations that these rays find on the retina are unique for each position that an eye can achieve in space. Moving the head changes the angles of entry of these rays into the eye and hence of relative locations on the retina. For example, as I sit here and I move my head slightly to the left I see the computer-screen also move relative to a particular place on the wall behind the screen. If I move my head downward I perceive predictable changes in the visual scene again.

The pattern of rays experienced this way is termed the optical array and it provides a unique specification of the location of the eye in space. The changes in the optical array when the eye is moved from one place to another are called the optical flow. The crucial point is that vision provides not only an indication of movements in the outside world but is also a rich source of information concerning our own movements in that world. The moving optical flow not only tells me about my movements in the environment, but it also tells me about the environment in ways that I could not achieve if I were not moving at all.

Hence, this view learns that vision is not merely an exteroceptive sense, passively informing the subject about changes in the environment, but that it is also a proprioceptive sense telling the subject about his own movements. Against this background Lee (1980) argued that we should add the term exproprioception to Sherrington's original list (interoceptive, exteroceptive, proprioceptive).

In the Gibsonian (or ecological) view movement and vision are very closely and reciprocally linked. For example, it is stated that visual information plays an essential role in the regulation of movements, particularly in the maintenance of balance.

Standing (but also sitting) involves continuous compensatory adjustments of the musculature. Any sway of the body away from the vertical has to be registered and compensatory muscular adjustment have to be made to prevent that balance is lost. The classical view is that the information about posture comes from receptors in the vestibular canals and in the joints and muscles, particularly of the ankles and hips. According to this view, disturbances in balance are primarily compensated by means of reflex processes. Even if the eye is involved at all in balance, it is of minor importance compared with the mechanoreceptors since one can stand in the dark. However, this classical view can be criticized since there is a growing experimental evidence that vision does play a crucial role in the regulation of movement.

Lee & Aronson (1974) showed this in a beautiful experiment. They used the socalled moving room. The experimental situation was as follows. Subjects (in these experiments children in the age between 13 and 18 months) were standing on a stationary floor with their face towards a wall with a picture to make it more interesting. The experimental room comprising three walls and a ceiling could be moved forward or backward past the subject standing on the stationary floor. Consider a subject standing still in the room facing the closed end. Motion of the room forward in the direction he is facing will produce optic flow patterns that are similar to what normally would be perceived with backward sway. If he uses visual proprioception in maintaining posture, the visual information should induce muscular action to produce compensatory forward torque. The converse holds for backward motion of the room. The results indicated that this was exactly what happened. A forward movement of the room resulted in a forward sway or fall of the body, a backward movement, that is to say a movement towards the subject resulted in falling backwards. These results are interesting since they indicated the dominance of visual information compared to the information coming from the mechanoreceptors. Remember that the floor was stationary, hence no changes occured in proprioceptive information coming from the receptors in the ankle joints. Similar results were obtained with younger children who were capable of sitting but not standing (Butterworth & Hicks, 1977). These experiments seem to indicate that, for infants at least, visual proprioceptive information is more potent than mechanical proprioceptive information. In more recent experiments performed by Lee and his co-workers it has been found that adults show similar behavior to that of infants. The effect was found even when the experimenter warned the subject that he was going to try to make him sway by moving the room and that he should do his best to resist this by ignoring the room movement.

The role of visual information was further explored in a series of other experiments. Lee, Lishman & Thomson (1982) studied the behavior of long-jumpers. In the long-jump, the athlete sprints 30 to 40 mtrs and than has te leap off a narrow take-off board (20 cm wide). The accuracy of foot placement is essential. The athlete's toe needs to be as close as possible to the front edge of the board, since it is from this point that the length of the jump is measured. Hence, the act of long-jumping is a very demanding task. It is therefore surprising how accurately skilled long-jumpers can strike the take-off board, or in other words how do they determine the time-to-contact with the board? What form of visual information do they use?

To answer this question the reader should recall the concepts optical array and optical flow. Lee's very interesting statement is that the time-to-contact (Tc) can be determined by changes in the optical flow. When the dilation of the retinal image of the take-off board exceeds a critical value then certain motor systems are triggered. In another study Lee et al investigated the behavior of gannets diving into the sea. The birds dive steeply from up to 100 ft with their wings partly open to steer themselves and just before they reach the water surface (at up to 50 mph) they streamline their bodies by stretching their wings right back and go in like a spear. Again, the question is how do they know when to streamline themselves for entry, or in other words how is in this case perception coupled to action? Also in this case it could be indicated that the birds were using the same strategy as the long-jumpers. When the dilation of the water surface exceeded a critical value then they stretched their wings (Lee & Reddish, 1981).

It is clear that a similar mechanism can be assumed for the human being catching a ball, steering a car or a wheelchair or for a person regulating its balance. Changes in the optical flow informs the subject about movements of the body relative to the environment so that compensatory measures can be taken. From these and other behavioral experiments it is clear that vision can be viewed as an integral component of the motor control system. Besides this there is also a growing body of physiological evidence for the existence of fast acting visual-spinal pathways (see Nashner & Berthoz, 1978). For example, it has been found that optical information specific to a cat's orientation influences the activity in the cat's spinal motoneurons. A large disk of colored dots was rotated in front of a cat's line of sight to imitate the optical flow that would result from tilting. When the disk was rotated to the left (simulating a tilt to the right), the extensor reflexes on the right side of the cat were enhanced and the flexor reflexes on the left side were enhanced (Thoden, Dichgans & Savadis, 1977).

However, in spite of all these experimental data some caution is still necessary since the data are not unequivocal. For example, Brandt, Wenzel & Dichgans (1976) did not succeed in producing an opto-kinetic effect in 6-12 years old children. Also the conclusion of Lee & Aronson (1974) and Kelso (1982) that the infant's visual system is more highly developed and more reliable than its proprioceptive system needs some reply. Woollacott (1986) indicated that the proprioceptive activation of postural muscles seems to be prewired and becomes functional prior to the visual system. She showed that in four months old infants consistent and directionally appropriate neck musculature became apparent when vision was removed. Also the Gibsonian claim of perceptual dominance is not without problems. Dichgans, Diener & Brandt (1974) and Young, Oman & Dichgans (1975) indicated that the visually induced tilt increased markedly when the otoliths are placed in a less favourable position by lateral head tilt indicating a more hybrid control system.

However, in spite of the, sometimes, contradictory results concerning the precize mechanisms it seems wise to emphasize the clinical importance of the relationship between perception and action. It is clear that perceptional disorders have an impact on motor control (see also Bles & Brandt, 1986). Therefore the assessment of this relationship (also in terms of optic flow patterns) deserves more attention in rehabilitation medicine.

Several authors indicated alterations of visual perception in a large number of patients with brain damage (van Ravensberg, Tyldesley, Rozendal & Whiting, 1984) as well as disturbed balance regulation (Hocherman & Dickstein, 1984).

Besides this, it should be recognized that impairment of visual perception forms an important limiting factor in the effectiveness of rehabilitation (Lincoln, Whiting, Cockburn & Bhavnani, 1985).

Until now this assessment receives relatively little attention in the normal medical examination of patients suffering from the consequences of damage to the central nervous system.

Motor learning.

After this ouverture on perception and action, I will now focus on the therapy (or learning) process.
Rehabilitation can for a large part be conceived as a learning process. Learning refers to relatively stable changes in behavior as a result of practice. But what is learned when a patient becomes more skillful, has he learned to control his muscles in a more efficient way, or has he learned particular movements, or has he learned internal references or motor programs? In this section an attempt is made to answer this question. The answer has direct relevance for rehabilitation therapy and indicates that in many cases therapy takes place in a rather obsolate way.

Motor learning: the acquisition of internal references (the closes loop notion)

Adams (1971) presented a theory which he termed a closed loop theory on motor control. This theory implies that the continuous availability of sensory feedback is necessary for motor control.
Any sizeable deficit in the flow or organization of afferent information (both proprioceptive and exteroceptive) will result in a disturbance of skilled motor performance. In his terms, motor learning can be understood as the acquisition of a memory trace and a perceptual trace for the movement under training. The memory trace can be understood as a "mechanism", whose role it is to select and initiate the response. The memory trace is, in fact, a motor program operating without feedback (the term motor program will be explained further in the text). Its only function is to start the movement. The strength of the memory trace can be viewed as a reference for adjustment of movements on the basis of received peripheral feedback. This perceptual trace is fundamental for Adams' learning theory, it is the internal reference for the correct movement. During therapy this perceptual trace develops and becomes more precise as a result of sensory feedback. Proprioception forms an essential source of sensory feedback, but visual, auditory and tactile information are also important for the development of the perceptual trace.
The more feedback is available, the stronger becomes the perceptual trace and the more efficient the process of error detection. Especially during the first phase of the therapy or learning process (which is called the verbal motor stage) when the perceptual trace has to be developed, feedback is essential.
The feedback is used to make the next response different from the previous one. The mechanism, responsible for evaluating the correctness of a particular response develops as a function of the sensory feedback impinging upon it. Without precise feedback the perceptual trace cannot be developed or forms

only a "weak" reference. Such a reference is a poor guide for responses and the result will be that performance hardly improves.

In Adams' framework therapy/training is the repetition of correct responses to strengthen the perceptual trace whereby the therapist/trainer functions as the primary supplier of feedback.

Research indicated that when precision is required as in relatively slow, goal directed movements such as a reaching for a glass, the concept of a feedback system, comparing the output of the system with an internal reference value (the perceptual trace) is necessary since corrections may be needed during the trajectory of the movement. However, it also indicated that with very fast, ballistic movements the notion of feedback as described above is limited in effectiveness.

Motor learning: the acquisition of motor programs (the open loop notion).

Consider a very rapid movement, in which the pattern of action is initiated and completed in 100 to 200 ms. There are many examples of movements like this in sports, take for example the a batswing in baseball (100 ms) or Muhammed Ali's left jab (40 ms). Feedback processes as suggested by Adams seem too sluggish for this type of control. Hence, in these cases it seems logical to assume that the central nervous system is capable of specifying the movement before it actually starts. The movement seems to be preprogrammed. A beautiful example of this can be found in an experiment performed by Wadman, denier van der Gon, Geuze & Mol (1979). Subjects had to perform a rapid elbow extension so that the hand came to rest in or near a target area. EMG's were recorded from the agonistic (m. triceps) and antagonistic (m. biceps) muscles. The results show the well-known three burst pattern. This was the normal condition (see Figure 1).

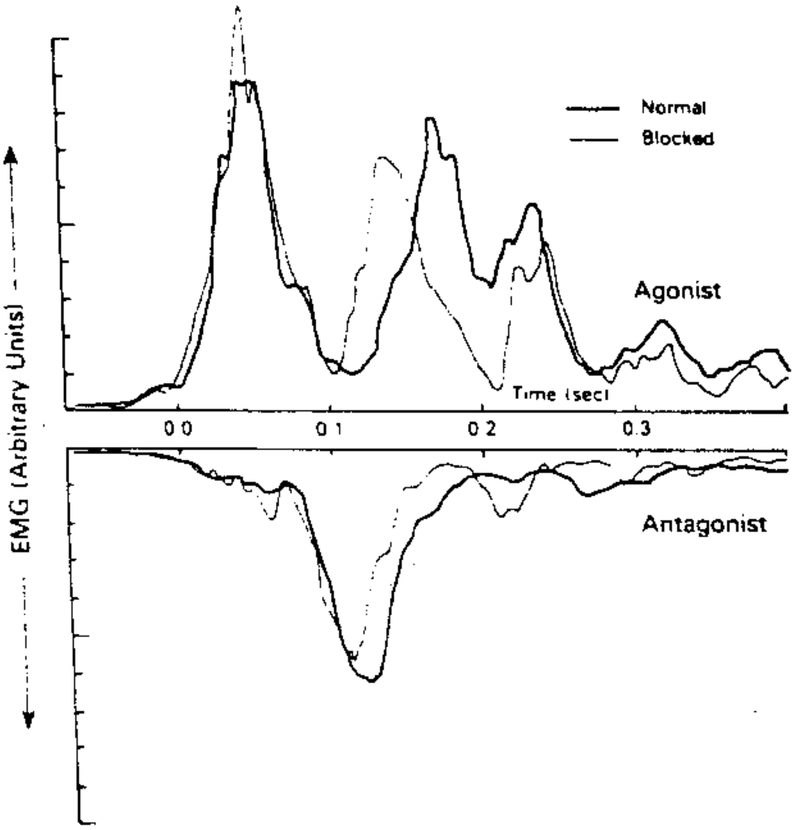

Figure 1 shows the integrated EMG activity. The normal curve represents the condition in which the extension movement was possible. The blocked curve represents the condition in which the movement did not take place.
Note that the during the first 100 ms the curves are almost identical. (From Wadman et al., 1979, Journal of Human Movement Studies)

However, sometimes the movement was blocked (of course the subject did not know this beforehand). The subject attempted to start the movement but this was impossible. Now, look at the Figure, there is something very interesting. When the curves "normal" and "blocked" are compared it can be observed that during the first 100 ms they do not differ. How can this be explained?
The best explanation is that (part of) the action pattern has been preprogrammed, structured in advance, and runs of as a unit without much possibility of modification from events in the environment. The results of Wadman et al are a strong indication for the existence of a motor program.
Traditionally the motor program has been defined as a sequence of stored commands that "is structured before the movement begins and allows the entire sequence to be carried out uninfluenced by peripheral feedback" (Keele, 1968, p. 387). However, although this might be the case in fast, highly overlearned movements, a strict application of this tenet to all movements is unacceptable, since for human beings there is no convincing evidence that sequences of movements can be performed without feedback. This does not imply that motor programs do not exist but it implies that the concept should be defined in a less strictly feedback independent sense.
According to this notion learning is the acquisition of motor programs. The problem for the subject in learning motor skills is to develop these open-loop programs to free him/herself from feedback involvement. Pew (1966) has shown, in a task requiring alternate finger-tapping movements to keep a dot central on the screen, that there was a clear shift from closed-loop (feedback dependent) to open-loop control.

Fundamental problems with closed-loop and open-loop theories.

There are three fundamental and closely related problems (see also Mulder & Hulstijn, 1984). First, I shall describe these problems and subsequently I will discuss in a possible solution. The three problems are: the problems of the degrees of freedom; the flexibility (or novelty) problem and the storage problem.

The problem of the degrees of freedom.
This problem was mentioned by Bernstein (1967). It is concerned with the very complex and unconstrained mechanical properties of the musculo-skeletal system: the number of different ways of moving - the degrees of freedom - is huge indeed for most movements. The higher levels of the central nervous system cannot be charged with specifying all the possible

details, with the whole set of possible commands. The question now is: how can such a flexible system be controlled?

The flexibility (or novelty) problem.
This problem refers to the fact that the same movement patterns can be performed with different muscle groups and to the fact that movements are never performed in exactly the same way twice. This flexibility problem is demonstrated in the following example (borrowed from Raibert, 1977).

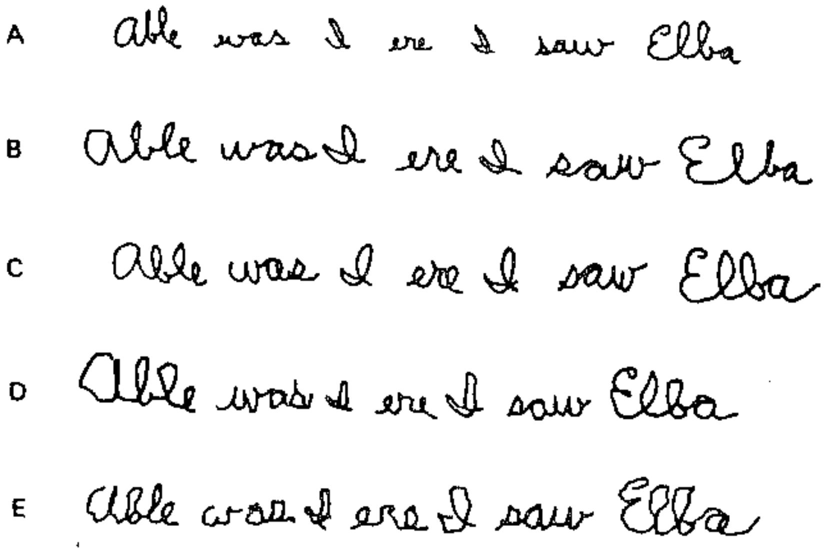

Figure 2 shows 5 different ways of writing the same sentence. In A writing is with the right (dominant) hand, in B writing is with the right arm, with wrist immobilized, in C writing is with the left hand, in D the pen was gripped between the teeth and in E the pen wastaped to the foot. The Figure clearly shows the muscle independency of motor control. (From Raibert, 1977, in Schmidt, 1982, Human Kinetics Publishers)

The Figure clearly shows that an individual retains the same unique style of writing regardless the employed muscle set (writing with the right hand, writing with the wrist immobilized, writing with the left hand or even writing with the pen gripped between the teeth or taped to the foot). This example indicates that we are able to perform novel movements immediately. It has also been demonstrated that intelligible speech can be produced when the articulators responsible for the act are obstructed, requiring the use of different vocal tract configurations to achieve the desired phonation.
These examples emphasize complexity and plasticity and are difficult to understood in terms of simple (muscle specific) control models. The basic question is how does the brain "know" how to control these novel movements.

The storage problem.
Both open-loop and closed-loop notion accept implicitly the idea of a separate trace or motor program for each movement. In other words they accept the idea of a one-to-one mapping between stored states and performed movements. For example in Adams closed-loop theory it is clearly proposed that the reference (the perceptual trace) develops through a learning process separately for each movement. However, if there exists a separate model or referrence in memory for every moment, our central nervous system should possess an almost inexhaustible storage capacity. For the speech production area, it was estimated by MacNeilage & MacNeilage (1973) that for the English language 100.000 phonemes were required and thus the same number of stored states. When we add this to the nearly countless additional ways in which human beings move their musculature, the individual must have an inexhaustible supply of either motor programs or feedback states. Although there is no evidence that this is not the case, it is scientifically more parsimonious to suggest mechanisms that do not need this amount of storage space.

Motor learning: the acquisition of action schemata.

The abovementioned theories, in fact, represent the classical view on motor control. The nervous system is viewed as a gigantic warehouse of representations (perceptual traces, motor programs) of every moment the individual can possibly perform. The selection of movements is accomplished by selecting from the warehouse these movement representations that should be activated to fit ones immediate needs.
The problem with this view is obvious and has already been mentioned. Since we are capable of performing an almost infinite number of movements it is extremely unlikely that our nervous system stores the representations of each specific movement.
Therefore we are forced to accept a constructional view on motor control. Movement representations are not available in ready-made form but have to be constructed according to stored rules. Hence, not the final "products" are stored but the rules for constructing them.

The constructional "view" action schemata.
The schema theory was presented by Schmidt (1975) to provide an answer to the abovementioned problems. Schmidt rejected the idea of a one-to-one mapping between programs and movements. He suggested the existence of generalized motor programs and schemata.
The schema idea, originally stated with respect to perception, is that in order to perceive a set of visual stimuli and to classify these stimuli correctly in a certain category we need not have previously perceived the particular set of stimuli in question.
The following example can explain this: when you see a dog, how do you know this animal is a dog even if you did not see this particular dog before? (Think of the analogy with movement flexibility: how can you perform a movement you never

made before?). A one-to-one mapping approach would accept the storage of a visual image of each dog you ever saw. However, this cannot explain the correct identification of a totally new dog. The idea is that you do not store "dogs" in memory, but prototypical abstract knowledge about dogs. The "broadness" of this knowledge depends on how many different types of dogs you have seen in your live. Have you met only a limited number of different dogs, the prototypical knowledge concerning dogs will be rather limited. This prototypical knowledge is termed the schema.

Schema formation.

How does a schema develop? Basically, when the individual makes a movement four things are stored in memory:

- The initial conditions: information about the muscular system and the environment.
- The response specifications: speed, accuracy, force, direction.
- The sensory consequences: the response-produced sensory information, that is, the actual feedback from eyes, ears and proprioceptors.
- Response outcome: information about the success of the response in relation to the outcome originally intended.

These four sources of information are stored after the movement is produced. When a number of such movements have been made an abstract relationship between the four sources develops. The strength of the relationship increases with each succesive movement of the same response class and is strongly correlated with the accuracy of the feedback information. This abstract relationship is the schema.

The motor program redefined.

To solve the storage problem Schmidt (1975, 1976) introduced the concept of a generalized motor program regulating a class or catagory of movements. For example, there are no x motor programs for the x ways of throwing a ball but a single program for this category of movements. The generalized motor program is considered as an abstract memory structure representing a raw, prototypical program. By manipulating various parameters (or response specifications) the same program can be employed for several movement outcomes. For example, by changing the parameter force the same "throwing program" can be used for throwing an object over various distances. By means of the schema rules these parameters are selected.
Many is unknown about the content of such a program. According to some authors it contains information concerning the temporal structure of the action (Van Galen & Teulings, 1983; Van Galen & Wing, 1984) or force/time relationships (Schmidt, 1980) or "topological" information (Bernstein, 1967).
Keele (1981) presented a version of the motor program in which the program controls the proper sequence of the action to be generated. In the present chapter it is also argued that the main function of a motor program is to regulate the order of the action elements. For example, consider the writing of the

letter "L". The normal sequence is from top to bottom and then from left to right. However, it can be written large or smaall, with the left or right hand etc. Hence the actual execution of the movement is extremely flexible. It seems logical to argue that the employed muscles are not specified in the program, they are too variable and depend largely of the actual requirements.
Hence, the order is programmed not the specific muscles. Which muscles are chosen forms a "lower order" control problem and depends on environmental conditions.

Rehabilitation therapy as the (re-)acquisition of action schemata.

Schmidt (1975, 1976) argued that the learning of motor skills could be understood in terms of the acquisition of schemata or rules. This idea was a fundamental break in the tradition whereby motor learning was considered to be the establishment of specific perceptual traces or muscle specific motor programs which defined only a particular movement. The schema theory implied that motor programs were generalized and that complex rules had to be formed to run these programs.
This theory has clear implications for rehabilitation therapy. The development of a schema is positively influenced by the following factors:

- Variability of practice;
- The consistent use of feedback;
- A close relationship between the therapy and the activities of daily living;
- The emphasis on active movements instead of passive guidance.

Variability of practice.

If during motor learning we are acquiring action schemata, this immediately implicates that learning by means of repetition of separate movements will be useless. Indeed, as in the case of "dog recognition" a rich (movement) experience is necessary to develop a schema. In other words, if therapy is the acquisition of schemata or prototypical knowledge about the skill under training then it is predicted that the "quality" of the acquired schema depends largely on the variability of practice. Patients, receiving variability of practice should perform novel motor tasks (within the same response class) better than patients who were exercised under a constant practice regime (repetition of the correct movement). Experimental evidence for this prediction has been found particularly with children (Shapiro & Schmidt, 1982). Perhaps this can be explained from the fact that in most of the experiments the tasks were very simple. Hence, adults had already established the schemata for performing these simple experimental tasks. Therefore no real learning (schema formation), was required. For the children the situation was different. Since they did not possess a large set of already developed schemata, for them the situation possessed a clear learning component. However, therapy with patients suffering from motor disorders contains also a large learning component, patients have to acquire novel motor skills and in this context the variability of practice seems to be still valid.

Rule 1: Therapy, as far as it concerns motor learning should be structured in such a way that practice takes place in a variable context.

The consistent use of feedback.

Normally our movements are accompanied by a continuous "stream" of afferent information. If the movement does not feel right, we try to adapt and correct the movement. The archer can see if the arrow is missing the target and can compensate in the next response. Even before we see the actual result of the movement we have an idea concerning the quality of it. People suffering from the consequences of damage to the central nervous system often do not have these normal sources of sensory feedback any longer. They are not aware what they do wrong to cause an imperfect response because their feedback loops are disturbed. In this case it is necessary for the therapist to provide relevant information. Without knowledge of results it is very difficult to develop an action schema since feedback (response outcome) is one of the four essential sources of information stored after a response. Knowledge of results about the outcome of an action is one of the most potent variables in learning. The knowledge of results provides information to the performer who evaluates this in relation to the desired goal. Designers of learning situations, as therapists are, should do everything possible to ensure that such information is available to patients (Mulder, 1985; Mulder & Hulstijn, 1985, 1987).

The following practical implications can be derived from the literature on feedback and learning. First, feedback is essential for improving performance and the more the better. But the feedback trials should be interspersed with no-feedback trials, so that the subjects are forced to learn to perform the task without the guidance provided by the feedback. Presenting without the guidance provided by the feedback. Presenting information every other trial or every third trial might be an effective method. Dependency on feedback should be avoided. Second, knowledge of results should be provided as soon after completion of the response as possible. This will maximize the learner's ability to associate the estimated response outcome information with the actual results of the performed movement.

Third, the interval between the presentation of the feedback and the start of a new attempt should be kept relatively free of other movements that could be confused with the target movement(s). Fourth, since the learner needs time to "construct" a new response, he/she should not be interrupted during the post-KR interval. Presumably, the more complex the task, the more critical the time needed for information processing. Learning appears to suffer from too short or filled post-KR intervals.

Feedback: information or motivation?

Often the role of feedback has been described in terms of motivation. In this view the knowledge of results functions as an external reward reinforcing the correct response. However, numerous lines of evidence suggest that humans do not use the feedback as a reinforcer or a motivational cue, but as a source of information about what to do next (Adams, 1971). This information processing orientation of feedback has quite important practical will tend to bias therapists away from post response statements such as "nice job" (reward) to statements containing more information concerning the desired outcome.

Rule 2: Therapy should be structured in such a way that knowledge of results is always available for the patient, especially in the beginning of the learning process.

Verbal instructions and demonstrations.
The most popular methods for conveying information about the goal and appropriate action sequences are verbal instructions and demonstrations. To instill in the learner the nature and the goal of the act therapists often resort to demonstrations. This is accomplished either live by the therapist or a filmed demonstration may be given with or without augmented instructions. There is evidence that modelling techniques are important for the acquisition of motor skills. For example, Landers (1975) performed a study employing the Bachman ladder.
Three groups had to climb the free standing ladder as high as possible. All the groups received verbal instructions, but the groups differed in terms of when an additional live modelling demonstration was given. One group was given the demonstration before any practice began, the second group was given the demonstration midway through the practice sequence and the third group was given the demonstration both before and midway through practice. The results showed that the two groups who received modelling before the start of practice performed more effectively than the group who started with only the instruction. In another study, Landers & Landers (1973) showed that for low-skilled subjects, the use of a peer model was more effective than the use of a teacher model, the reverse was true for high-skilled subjects.
Several authors indicated the relevance of observational learning for the motor skills area (Carroll & Bandura, 1982, 1985; Whiting, Bijlard & den Brinker, 1987). It is therefore surprising to discover that in (physical) therapy this learning procedure (using video tapes or live models) is hardly employed. This is surprising since the human being is particularly well "equiped" to transform observations immediately into the correct actions.
Meltzoff & Moore (1985) described how newborns are already able to imitate facial expressions, that is, are able to translate visual information immediately into motor patterns. In very much the same way patients who have reached a certain level of functioning can be employed as models for patients who had not reached this level. The latter patients can be instructed to imitate the "higher skilled" subjects.

Rule 3: Therapy should make more use of observational learning procedures.

A close relationship between the therapy and the activities of daily living.

Recall that it was argued that separate movements play no role in the learning process. No muscle-specific combinations are learned but goal directed actions. These actions are represented in memory by means of action schemata. However, the use fulness of these action schemata depends largely of the structure of the therapy. A therapy focussed on the level of muscles and movements, that is, aimed at restoring destorted elements instead of destorted actions will result in the development of a very "narrow" schema. Such a "narrow" schema is of almost no use in daily live. To improve the generalization value of the acquired schema a patient should be exercised in a situation resembling as close as possible the daily world. If the gap between the therapeutical situation and the daily life situation is large, the schema acquired during therapy will be of no use for the activities of daily life. The number of identical elements across the two situations is too limited so that almost no transfer takes place from one to the other learning situation creates an artificial learning situation with minimal long term effects.

Rule 4: Therapy should be structured in such a way that a maximum overlap is realized between the therapy situation and the daily live situation ("law of identical elements").

Active movements vs passive guidance.

A technique frequently used in therapy involves guidance, whereby the learner is in some way guided through the task. Although such a procedure may have positive effects on the mechanical consition of the muscular system it has hardly any learning effect (Newell, 1981, Levitt, 1982). A major conceptual problem with guidance in a learning context is that it eliminates the learner's need to select the appropriate response.

Rule 5: Passive movement does not result in learning.

Stages in learning.

Three stages can be distinguished in the learning process. The first stage is termed the verbal motor stage or the cognitive stage. During this first phase the patient has to understand the meaning and the goal of the therapy. Considerable cognitive activity is required, good strategies have to be retained whereas inappropriate ones have to be discarded. During this phase the performance of the patient is usually very inconsistent because he/she tries many different ways to reach the goal. It is extremely important that in this first phase the therapist provides the patient with sufficient sources of feedback. During the first phase of the therapy process a global idea concerning the correct action has to be developed, a cognitive representation that can function as an internal model or reference for action. The feedback of the action is compared against the internal model. If in this stage such information is not available or insufficient or inconsistent, the development of such a crude first reference is impossible. It is the therapist's responsibility to deliver this information.

Verbal activity from the side of the learner plays an important role in this first phase. The learner uses self-instruction as an method to guide his attempts.

The second phase in the acquisition process is termed the motor stage or association phase. This phase starts when the individual has acquired an effective way of performing. The performance is more consistent and the attentional load of the task has been reduced. Practice should take place in a daily live setting to strengthen the schema further.

The third stage is termed the autonomous phase. Now, the skill has become more or less automatic. Sometimes it takes hundreds or thousands of repetitions to reach this final phase.

Recent developments in motor control theories.

The notions so far discussed are all cognitive, that is to say, they all accept the existence of a complex set of internal (mental) processes. Some psychologists have criticized this approach and defend a more biomechanical notion based on the work of the russian scientist Bernstein (see Kelso, 1982, part V).

Bernstein discussed the study of movement in terms of the problems of coordination and controlling a complex system of biokinematic links. He understood that the focus of analysis could not simply be the muscular forces provided by the organism but must include inertia or reactive forces. Bernstein's work was focussed on the degrees of freedom problem. This problem constitutes a very difficult and fundamental puzzle for students of movement. The problem is also of relevance for rehabilitation therapy. Let me explain this in more detail. As we have seen, Schmidt (1975) solved the degrees of freedom problem by introducing the schema as a cognitive concept. The Bernsteinian approach takes another route. Consider the control of an individual arm. The arm consists of a shoulder, elbow, radio-ulnar and a wrist joint. Now consider we want to control this arm, what sort of problems do we meet? (the example is literary borrowed from Turvey, Tuller & Fitch, 1982, p. 241-242). The shoulder joint can change on three axes, that is to say when the arm is fully extended it can still vary its position to the right and left, upward and downward and it can rotate about its length.

Hence, the shoulder joint has three degrees of freedom. The elbow has only one degree of freedom, whereas the wrist joint has two degrees of freedom. Consider that the units of control are the joints than the central executive has a problem to solve with 7 degrees of freedom. Now consider the muscles as the inits of control. In that case the problem is much more complicated, since there are 10 muscles working around the shoulder joint, 6 muscles working at the elbow, 4 muscles are responsible for the working of the radio-ulnar joint and finally 6 muscles move the wrist.

Here we have a problem with 26 degrees of freedom. The control problem is of astronomical and bewildering complexity for theories accepting the individual motor units as the elements of control. Hence, thekey problem for the central nervous system is how to reduce the degrees of freedom problem, or in other words how to reduce the control problem. An interesting hypothesis is that nature solves this puzzle for us by keeping the degrees of freedom individually controlled at a minimum by using "functional units" defined over the motor system that automatically adjust to each other and to changes in the field of external forces.

These functional units (also termed coordinative structures) develop during a learning process. Turvey et al described the difference between a novice in (gun)shooting and a skilled marksman. What makes these two persons different? When observing the novice it can be seen that the arm is not stable, there is a tremor and the muscles are not "linked" to each other. The skilled marksman, on the other hand, is able to stabilize the body. Deviations in one part of the muscle-joint complex (e.g. wrist) are immediately compensated by a movement in the shoulder.

Hence, the muscle-joint complex functions as a unit. What previously was a system with many degrees of freedom (the relative independent function of the separate muscle-joint combinations in the novice) now becomes a system of fewer degrees of freedom. Here we have a fundamental principle which states that the number of degrees of freedom of the system controlling action is much less than the number of mechanical degrees of freedom os the controlled system (Turvey, 1977). Learning can be characterized as a process directed at reducing the degrees of freedom and the development of coordinated structures.

Coordinative structures have their origins in the relative autonomous subsystems of the spinal cord. The rol of higher levels of the nervous system is to modulate interactions within and among neural mechanisms at the spinal level. It is important to note that this system can be "prejudiced" towards executive intentions. The process of biasing is termed tuning. Tuning can, for example, take place by means of visual input. This optical input (recall Lee's experiments described earlier in this text) tunes or prepares the spinal control systems. Optical information can affect muscle reflexes in human subjects.

Take for example the following experiment in which subjects were asked to fall forward, hands first onto a platform. The platform could be tilted at various angles away from the body. The EMG activity in the m. triceps was monitored during the self-initiated fall toward the platform. When subjects were able to see the platform, the time of the onset of the EMG activity varied so that it always began a constant amount of time before impact, regardless how far awayu the platform was. However, if the subjects were blindfolded and had no way of knowing when impact would occur the muscle response time was stereotyped, starting always at the beginning of the fall (Dietz & Noth, 1978).