

BRAIN STRUCTURES PARTICIPATING IN MENTAL SIMULATION OF MOTOR BEHAVIOR: A NEUROPSYCHOLOGICAL INTERPRETATION *

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This paper reviews findings from cognitive and sport psychology, as well as from neurophysiology, concerning mental simulation of movement. A neuropsychological hypothesis is advanced to explain why mental practice can improve motor skill learning. Mental practice activates certain brain structures selectively as shown by measurements of regional cerebral blood flow. It appears likely that this activation improves the subsequent control of execution of movements. It is pointed out that the study of simulation of movements may not only be of value for sport training but also have importance for the rehabilitation of patients with motor disturbances following lesions of the central nervous system.

1. Introduction

It is generally assumed that motor behavior requires the participation of parallel information processing in a cooperative distributed way. Thus, voluntary movements may involve several stages of information processing such as motivation, planning, cognition, programming and feedback regulation (Kornhuber 1984). These stages can be viewed as hierarchically organized, and as Pew (1984) argued against a serial model of information processing suggesting that the various levels in the hierarchy may operate more autonomously than has

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previously been assumed. In this perspective, the variety of centers of activity may be thought of as relatively autonomous structures which are coordinated by passing specifications to each other up and down the hierarchy. The analysis of the cerebral substrate of voluntary motor activity should include a study of mental simulation of motor behavior, also called 'mental practice' or 'mental rehearsal'.

Mental practice can be defined as an imagined rehearsal of a motor act with the specific intent of learning and improving it, without any simultaneous sensory input nor any overt output, i.e. any muscular movements (Richardson 1967a,b). It constitutes a 'pure' cognitive activity. Many authors have focused their attention upon the dynamic mental imagery which may act as a device enhancing the memorability of serial spatial and kinesthetic information (Denis 1985). More generally, imagery includes cognitive processes which allow human beings to anticipate their actions, or to project their thoughts into the future in order to make plans and to define goal-directed cognitive as well as behavioral strategies (Ingvar 1985).

In this article we shall review the evidence from cognitive psychology and sport psychology, psychophysiology and neurophysiology which suggest that mental practice might be considered as a neuronal process which involves specific brain structures. Apparently, these structures are of basic importance for the cognitive control and planning of movements. The structures in question also appear to participate in the execution of actual movements mediated by appropriate executive sensory-motor regions. As demonstrated recently mental simulation of movements does not only include cortical regions but also the cerebellum as well as some subcortical structures (Decety et al. 1988b).

This review considers the top-down approach from cognitive psychology and the bottom-up approach from neurosciences as complementary in order to explain the positive effects of mental simulation of movement (MSM) on motor performance.

2. Behavioural studies

2.1. Mental practice in sports training

Mental practice is an accepted procedure in the preparation of athletes (Suinn 1984). Such practice covers a warming up period, relaxation and concentration, and mental visualisation.

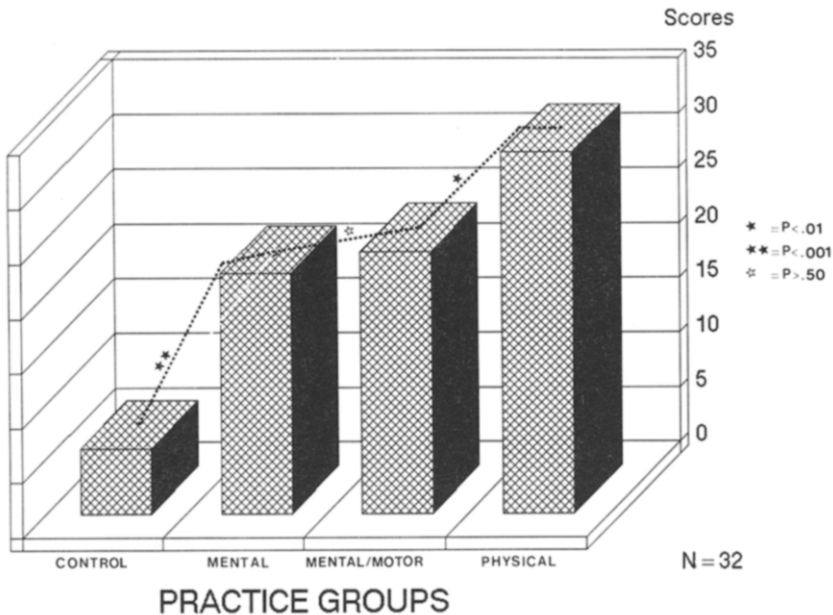


Fig. 1. Improvement scores in four independent practice sessions: control (no practice), mental (imagined throws), mental/motor (imagined throws and actual performance), and physical practice. The task was throwing darts at a target. p levels correspond to the analysis of variance. (Adapted from Mendoza and Wichman 1978, with permission.)

The present review will be focused on visualisation of movement since this has been the main component investigated so far (Denis 1985).

The basic paradigm in a number of studies of mental practice requires a minimum of three conditions. First the subjects are tested on a given skill. Then they are randomly allocated to three groups (according to the condition of training). One group does mental practice, one carries out actual physical practice of the skill, and the third one, the control group does not perform any training. The three groups are tested again during performance of the skill, and the improvement is scored. Several studies (Twining 1949; MacBride and Rothstein 1979; Mendoza and Wichman 1978) have shown that mental practice produces significantly higher scores than the control conditions, while physical practice produces significantly higher scores than mental practice. This is illustrated in fig. 1 from Mendoza and Wichman (1978).

Other studies have demonstrated that physical practice does not give different results when compared to mental practice. Both produce

higher gain scores in comparison to the control condition (Clark 1960; Rawlings et al. 1972; White et al. 1979; Wrisberg and Ragsdale 1979; Kohl and Roenker 1980).

A third group of studies concerns mental practice combined with physical practice. Such a combination produces significantly higher scores than physical practice alone (McBride and Rothstein 1979; White et al. 1979).

Thus, it is evident that mental practice improves skilled motor performance. Furthermore, mental practice seems to be more efficient for skills which do not require a permanent sensory feedback information like athletics, diving, swimming, gymnastics, which rely primarily on a so-called outflow processing, i.e. a skill which emanates from the brain and follows a preplanned complex motor sequence (Decety and Mick 1988). Indeed, the expected sensory consequences of the movement are not accessible in mental practice.

3. Cognitive models

3.1. Components of a motor skill

It seems relevant to differentiate between a cognitive and a motor component of a skill, although they appear to form a continuum (Schmidt 1975). This assumption is supported by studies which have shown that mental practice facilitates learning of tasks in which the cognitive component is interdependent with the motor one. Rotary pursuit tracking, or gymnastics have been studied in this respect (Phipps and Morehouse 1969; Rawlings et al. 1972; Minas 1978; Wrisberg and Ragsdale 1979; Kohl and Roenker 1980; Ryan and Simons 1981 and 1983).

All these studies demonstrate that mental practice improves motor performance, most likely by an inner rehearsal of the cognitive component of a motor skill. Accordingly, the initial stage of motor learning which has been assumed to be controlled largely by verbal/cognitive activity rather than peripheral processing (Adams 1971) should benefit more from mental practice.

During mental simulation a performer may make use of verbal planning. Hence, verbal encoding may participate in mental practice to a smaller or greater extent. Indeed, verbal conceptualisation is known

to be a part of the plannification of a motor task in the early stage of learning (Adams 1971; Schmidt 1975). Thus, it is appropriate to discuss the verbal part of the cognitive component in mental simulation of motor behavior. To what extent is a subject carrying on his mental training with the help of 'silent speech' (Ingvar 1983). Indeed verbal instructions can be mentally rehearsed from previous verbal commands given by e.g. a coach. This verbal component of motor learning can only here be commented upon very briefly. However, it should be recalled that human voluntary actions are dominated by language in the sense that language often precedes action and forms a part of it (Jeannerod 1983). Furthermore, motor programs can be seen as part of the meaning of verbal items that represent actions (Engelkamp 1986).

In this context, Feltz and Landers (1983) have found positive effects of mental simulation both in earlier and later stages of learning. Savoyant (1988) proposed that in early stages of learning, mental simulation may contribute to the primary construct of the cognitive elements of the action (as a model), while in later stages it might contribute more to the refinement of motor programming and control. In that case, the contribution of the verbal component might be mainly active in the early stage of learning. This assumption would, however, need further analysis.

The majority of experiments indicates that mental practice is better than no practice. When one analyses the effects of various types of cues used in these studies, it appears that visual cues are by far the most efficient aid to mental practice. This suggest that mental practice involves a visual process. Therefore, it is relevant to discuss the visual imagery process operating in MSM.

3.2. Visual imagery of movements

Mental practice involves mainly visual and kinesthetic imagery. The importance of each of these components depends on the instructions given to the subjects. One of the most common instructions to subjects during MSM is to imagine that they are in the task environment performing the task itself.

According to Kosslyn (1980, 1981) mental imagery must be viewed as a composite brain activity which requires at least four classes of information processing: those involved in image generation, inspection or transformation and those which determine when imagery will be

spontaneously used. People differ in their imagery ability with regard to these four classes of information processing (Kosslyn et al. 1984). It is therefore not surprising that the ability for visual or kinesthetic imagery correlates with the success of mental practice (Marks 1977; Housner and Hoffman 1981). There are, however, also some experiments in which no correlation was found (Ryan and Simons 1981; White et al. 1979). This failure can be explained by the weak validity of the questionnaires used to establish imagery ability (Hall and Goss 1985). Several studies have supported the view that for a mental image to serve efficiently in mental practice, it should possess three properties: vividness, controllability and an exact template reference image (e.g. Marks (1977) for the vividness, Richardson (1969) for the controllability, Finke (1979) and Johnson (1982) for the template factor, for a review see Denis (1985)).

Cognitive scientists appear to agree on three main characteristics of mental imagery.

(1) It has been shown that there is an intimate relationship between perceptual and imagined processes. Finke (1980) has reviewed this for pattern information in the visual system.

(2) Imagery competes with perceptual tasks, possibly due to the fact that they use common mechanism and/or resources, such as attention and the central executive component of a working memory (Phillips and Christie 1977). Thus perceptual and imagined processes have mutually competitive effects on each other, a phenomenon called selective interference.

(3) Selective facilitation is the last functional characteristic. Visual imagery can facilitate perceptual processes. Finke (1986) has demonstrated that mental imagery may enhance the perception of an object by causing a selective priming of appropriate neural mechanisms in the visual system.

Mental practice might gain from taking all three components into account in order to improve motor performance as suggested by Decety and Mick (1988).

Recent theories of action attribute a central role to visual imagery in the initiation and direction of action plans of higher order which in turn initiate and control trains of motor commands (Gopher 1984). Kelso and Wallace (1978) have developed a vision-based theory of

action in which imagery generates anticipatory signals which prepare executive mechanisms to accept certain kinds of information (priming). Johnson (1984) showed that the bias produced by imagery could be suppressed only by a concurrent visual-spatial task and not by a motor task, which further supports a visual-spatial basis for MSM. Nevertheless, while much has been written concerning the visual-spatial processes involved in MSM, other explanations have been proposed in the field of motor behavior in terms of inflow or outflow processing.

3.3. Inflow or outflow processing?

Since the human motor system is a very complex whole with many interacting parts, processes and mechanisms it is useful to consider various modes of control and examine them somewhat independently (Schmidt 1988). The effects of mental practice on motor skills have been interpreted as either due to (a) an inflow processing, that is a closed loop system requiring proprioceptive and peripheral feedback (Adams 1971), or due to (b) an outflow processing, i.e. an open loop system depending on a pre-planned serial movement sequence (Lashley 1951).

(a) The inflow explanation is based mainly upon the finding that motor imagery is accompanied by some electromyographic (EMG) activity in specific muscles pertaining to the simulated motor act (Jacobson 1932, 1973; Freeman 1931). The kinesthetic feedback from the slight muscle activity has been presumed to facilitate the imagery processes. Epstein (1980) showed that there is a correspondence between the amount of myoactivity during mental practice and skill attainment. He also showed that 'first person' kinesthetic imagery was more effective than third person imagery. Wehner et al. (1984) have reported that the myoactivity during mental training clearly shows a task-specific frequency distribution. However, they consider the peripheral EMG activity during mental practice more as a paraphenomenon or an 'effect-mechanism', a consequence of the imagery rather than a primary cause of the imagery.

(b) The outflow explanation is founded on the prediction that mental practice is more effective in the early stages of motor learning (Schmidt 1975) and that imagery improves the cognitive component more than the motor component of the skill (Minas 1978; Wrisberg

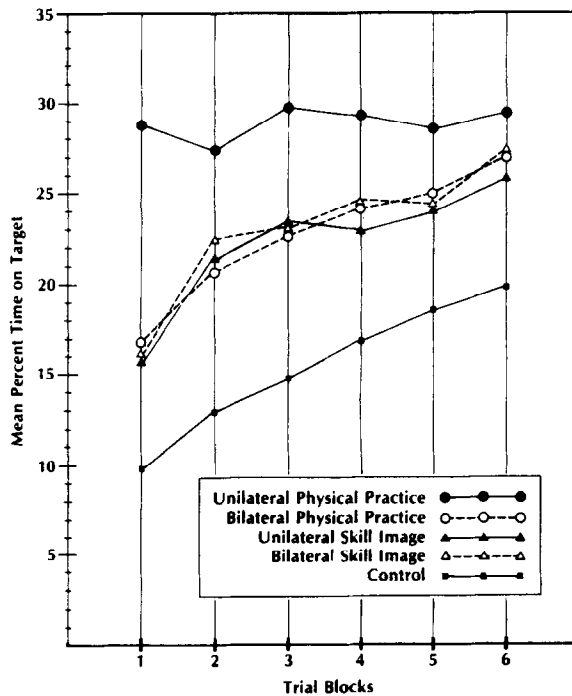


Fig. 2. Post-rest mean percent time on target as a function of treatment conditions and trial blocks in a rotary pursuit task ($N=100$). Analysis showed an overall effect of treatments, $F(4, 94) = 6.61$, $p < 0.05$. A subsequent Newman-Keuls test ($p = 0.05$) performed on this effect revealed that the four groups performed at a higher level than the control group. (From Kohl and Roenker 1983; reproduced with permission.)

and Ragsdale 1979; Ryan and Simons 1981, 1983). Additional evidence for this view comes from studies using a bilateral transfer paradigm. Transfer is usually defined as the gain (or loss) in the capability for responding in one task as a result of practice or experience on some other task (Schmidt 1988). This procedure is presumed to demonstrate predominantly inflow mechanism when the learned motor responses are only minimally transferred to the contralateral limb. It is thought to show an outflow mechanism when there is a substantial transfer contralaterally (Kohl and Roenker 1983). During skill imagery (fig. 2) there is a significant positive transfer, and no difference between unilateral and bilateral transfer as shown by Kohl and Roenker (1980, 1983).

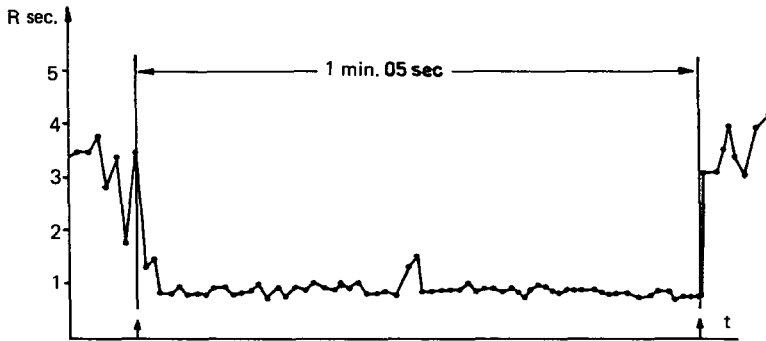


Fig. 3. Increase of the respiration frequency during mental practice of swimming a given distance in a predetermined time. *R* denotes the duration of the breathing movements in sec. Vertical arrows and lines indicate start and end of the mental imagery of swimming. (Pickenhain and Beyer 1979; reproduced with permission.)

However, the data quoted from the physical practice groups revealed a significant difference between unilateral and bilateral transfer. Thus both inflow and outflow processing might be involved in mental practice.

The outflow explanation is supported by the strong interconnection between motor commands and autonomic changes. There exists a correlation, for example, between real swimming movements of the arms and the respiratory rate. The same autonomic effect were observed in subjects simulating mentally that they were swimming a given distance (Pickenhain 1976; Pickenhain and Beyer 1979).

The respiration frequency curve (fig. 3) shows a strong acceleration coinciding with the frequency of the mentally executed arm movements. In the middle of the distance (the moment of the turn) a short deceleration of breathing can be seen.

The timing of the movements executed mentally has been investigated only to a limited extent, although the temporal organization of motor sequences is a crucial parameter in both actual and imagined motor behavior. In athletes, it was found that the time required for a subject to imagine that he is walking up to a given target was close to the real movement time (Decety et al. 1989). The same finding was made in subjects imagining that they performed a graphic gesture (Decety and Michel 1989). This temporal feature of mental simulation of movements suggests that there is a central mechanism responsible for the timing (temporal organization) of motor simulation and that it

might be identical both for the actual performance of a motor act and mental simulation of movement. This interpretation would be compatible with the above-mentioned outflow processing model and also compatible with the neurophysiological evidence summarized below. We suggest that the programming of motor acts or imagined behavior share the same timing mechanism. Therefore, one would like to argue that not only perceptual memory systems are involved in MSM but also to some extent some specific motor processes as it will be developed in the next section.

4. Neurophysiological correlates

4.1. Neurophysiology of mental simulation

The part of the cortex in front of the primary motor cortex consists of two main subdivisions: the supplementary motor area (SMA) and the premotor cortex. They are since long assumed to play a role in the programming and control of voluntary movement (Penfield and Rasmussen 1950; Evarts 1984; Roland 1984). It is therefore close at hand to assume that the two premotor regions are involved in mental simulation of movements. There is in fact direct neurophysiological evidence that this is so.

Since the development of the $^{133}\text{Xenon}$ regional cerebral blood flow (rCBF) technique (Lassen and Ingvar 1961; Ingvar 1962), numerous studies have demonstrated regional cortical functional changes during voluntary movements. Thus Olesen (1971) and Ingvar and Lassen (1975) showed that hand movements augmented the flow in the contralateral hand area. Roland et al. (1980) extended these studies and showed that during unilateral mouth, hand and foot movements an rCBF 'homunculus' can be demonstrated in the contralateral rolandic region. Furthermore, they showed that while unilateral sequential hand movements caused the flow to increase in the hand area contralateral to the movement side, there was at the same time a bilateral activation of the SMA. In contrast, an isometric (non-sequential) hand contraction gave only an activation of the contralateral hand area. With positron emission tomography (PET), Roland et al. (1982) also showed that voluntary sequential finger movements gave bilateral activation of the basal ganglia in addition to the cortical flow changes.

In the present context, rCBF measurements during motor ideation are of especial interest. In 1977, Ingvar and Philipsson for the first time measured rCBF in human subjects which were instructed either to imagine a clenching hand movement with a slow rhythm, or actually to carry out the same movement. During mental simulation they found significant flow increases in the premotor and frontal regions (which amounted up to + 30%) in some areas. When the hand movements were actually carried out there was mainly a rolandic activation of the same magnitude. Later, Roland and collaborators (1980, 1982) asked normal subjects to imagine a rapid and skilled sequence of digit movements. They found a significant and localised rCBF change mainly in the supplementary motor area. The results of Roland et al. (1982) thus confirmed that the SMA plays an important role for the internal programming and simulation of complex motor sequences. On the basis of the findings mentioned and from theoretical consideration of the physiology of voluntary movements, Eccles (1982) has suggested that the SMA may act as a bilateral interface between the concept formation and the actual execution of motor acts.

In a recent study of Roland et al. (1987), the rCBF and the regional cerebral oxidative metabolism ($rCMRO^2$) were measured in normal volunteers with ^{15}O and a PET technique. The subjects were asked to imagine visually that they were walking along a well-known route in their home town. They were specifically instructed not to imagine their own movements during the imagined walk. The cortical areas which became active were located prefrontally in both hemispheres, in the frontal eye fields and in the occipital areas. However, the most pronounced flow increase appeared in the parietal cortex. Subcortically, the $rCMRO^2$ increased bilaterally in the neostriatum and in the posterior thalamus.

Measuring rCBF with $^{133}Xenon$ and a gamma camera, Decety and Philippon (1988) studied normal subjects imagining a graphic movement (writing 'one, two, three, etc.') either with the right or the left hand. The subjects were instructed to imagine the movement at the 'first person perspective' and to try to 'feel their writing hand'. Regions corresponding to the prefrontal cortex, the supplementary motor area, and also the cerebellum were activated significantly. The participation of the cerebellum has been confirmed recently. Using the single photon emission computed tomography (SPECT) during MSM of a tennis training in normal volunteers, Decety et al. (1988b) observed a signifi-

rCBF increase during motor imagery

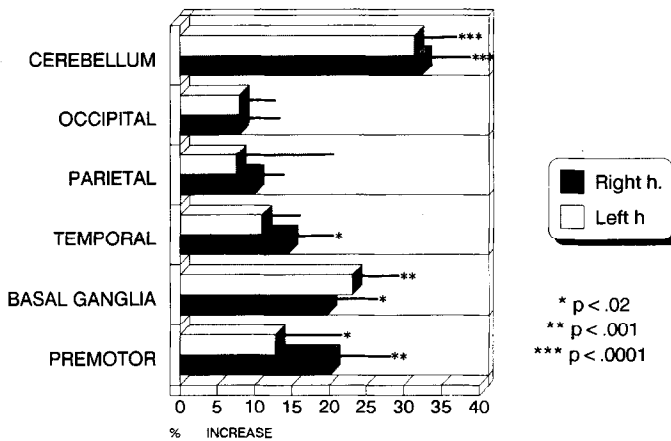


Fig. 4. rCBF increase during mental simulation of a tennis training in 12 normal young volunteers (19–28 years). Measurements made with a SPECT camera and the intravenous injection of ^{133}Xe . Percent of increase is calculated from rest. Statistical analysis made with Student's paired t test. (From Decety et al. 1988b.)

cant rCBF increase bilaterally in the cerebellum ($p < 0.001$), as well as in the basal ganglia ($p < 0.01$).

The rCBF studies quoted are in general supported by several electrophysiological investigations which are consistent with the idea that structures in the region of the SMA and the prefrontal cortex play an important role in motor preparation (for a review see Brunia 1987). Thus, studies of slow-wave potentials, including the 'contingent negative variation (CNV)' (Walter et al. 1964), and the readiness potential (RP) preceding voluntary movements (Kristeva et al. 1979) have indicated a role for this part of the cortex in the preparation for movement. The RP, which is considered the electrophysiological counterpart of the initiation of a movement, usually starts about 1500 msec before the onset of a simple movement (Eccles 1982). Its maximum is over the anterior midline of the head. The potential distribution has been demonstrated to be different for hand and foot movements (Brunia 1980). Amplitudes are larger over the hemisphere contralateral to a finger flexion while CNV amplitudes preceding right foot movements were larger over the right hemisphere than over the left one (Brunia and Vingerhoets 1981; Brunia and Van den Bosh 1985). These authors

proposed that the larger CNV amplitude over the hemisphere ipsilateral to the movement side of the foot might reflect a predominant brain activity in the contralateral hemisphere since the dipole orientation for hand and foot movements is different. According to Brunia (1980) this is explained by the fact that the projection area of leg muscles is situated along the inner side of the fissura longitudinalis. The RP ends about 90 msec before the movement. About 55 msec before the onset, a well-localized potential begins over the precentral motor cortex, which reflect the firing onset of the pyramidal tract neurons. Subcortical mechanisms, mainly in the basal ganglia and the cerebellum, participate between the RP and the motor potential. This subcortical activity seems necessary to provide the spatiotemporal functions and programs for self-generated movements (Deecke and Kornhuber 1978).

4.2. Clinical correlates

In the present context, it is of interest that clinical observations show that SMA lesions cause a cessation of internally generated limb movements and spontaneously by produced speech lasting at least a month, and a permanent deficit in alternating movements of both hands (Laplane et al. 1977). Damasio and Van Hoesen (1980) found that patients with lesions confined to the SMA were not paralysed, but had lost their capacity to initiate limb movements as well as to speak spontaneously. Lesions of the premotor cortex give a stereotyped motor disturbance with weakness of the contralateral shoulder and with a disturbance of inter-limb co-ordination (Freund and Hummelseim 1985). This supports the notion that the SMA is of major importance for the planning and initiation of voluntary movements. The premotor cortex seems to be involved in the preparation of the motor acts by controlling especially proximal muscles and the timing of motor sequences.

In a recent report, Ward (1988) presented three patients with episodes of compulsory movements which could not be resisted in spite of great willful attempts. EEG and CT scan gave strong evidence that the cause was an active epileptogenic focus in the frontal cortex. This observation appears to be a positive counterpart of the negative symptoms following prefrontal lesions.

Clinical as well as experimental studies have thus in general indicated that the frontal lobes are involved in the highest level programming of goal-directed acts (Fuster 1980; Ingvar 1985). This includes the elaboration of complex long- and short-term plans for the internal manipulation and optimization of representational systems. A complete discussion of these hypotheses lies outside the scope of this review. Reference is made to the recent monograph about the frontal lobes edited by E. Perecman (1987).

5. Concluding remarks

There is general agreement in sport psychology that mental practice can improve both the acquisition and the performance of a motor skill. Mental simulation of movement can be viewed as a cognitive modelling of a motor act which requires several components such as motivation, attentional resources, visual and kinesthetic imagery, all contributing to the construction of an image of the given serial action making the skill easier to learn and to carry out. Although one of the main effects of MSM may be the result of the development of a mental model through perceptual organization which permit the performer to anticipate the appropriate response and its effects, one may propose that other mechanisms are involved.

Mental simulation of motor behavior seems to rely both on outflow and inflow processing which activate in a serial order components of a given motor program. Several specific brain regions appear to be involved in mental practice as suggested by both neurophysiological and neuropsychological studies.

We propose here that mental practice does not only involve the primary stages of motor programming as suggested by the prefrontal and SMA activations. Indeed, cognitive theories and empirical findings have stressed that the serial and dynamic aspect of cognition may participate in motor control (Stelmach and Hughes 1984). That leads us to consider mental practice as a virtual *simulation of motor behavior*.

Such an 'inner' simulation process, experienced consciously, requires the construction of a dynamic representation in working memory which makes use of spatial and kinesthetic components retrieved from long-term memory, as well as the activation of serial plans of action. Such processes apparently require internal intracerebral feedback loops which

involve subcortical structures (Roland 1984; Decety et al. 1988b) for actual movements. The cerebellum is known to be involved in the programming of movement (Ito 1984). Hence, its participation in mental simulation of motor acts (Decety and Philippon 1988; Decety et al. 1988a,b) is another recent piece of evidence supporting the hypothesis that widely distributed structures participate in the synthesis of the motor programs.

Much recent evidence demonstrates that a basic function of the frontal lobes is to control the temporal organization of behavior and cognition (Fuster 1980; Ingvar 1983, 1985; Goldman-Rakic 1987). This large part of the human cortex is the phylogenetically youngest part of the brain. It is characterized by a uniquely rich set of afferent and efferent projection systems linking it to virtually most other functional systems of the brain (Goldberg and Bilder 1987). Some basic concepts on the function of the human frontal lobes might be used here to consider the neuronal substrate of movement simulation:

(1) Motor simulation clearly requires a serial (sequential) organization of cortical neuronal events, into what is termed 'action plans'. This sequential processing may include several parallel sub-processes separately but simultaneously planned as it is for actual motor control (Jeannerod 1988).

(2) The temporal organization of mental simulation should, as pointed out, to some extent at least, involve the same neuronal substrate as the timing of the actual voluntary activity. Most likely the substrate for the timing of mentally simulated movements pertains hierarchically to a higher level than the level from which motor execution is controlled.

(3) The demonstration in recent measurements of rCBF in man that specific brain structures are activated by movement simulation has revealed new aspects of the highest processes which underlie voluntary motor activity.

On the basis of these points, one would like to suggest that simulation of movement (i.e. inner awareness of serial motor activity) is controlled by those parts of the frontal cortex which are specifically involved in the timing of cognitive and motor events. The evidence available shows that the prefrontal and the dorsolateral frontal cortex plays a fundamental role for this timing and also for the conscious awareness of mental simulation (Posner and Presti 1987). This hypothe-

sis thus suggests that the dorsolateral frontal cortex plays a role in the primary control of motor simulation. This may include a secondary usage of a somatosensory and visual information stored in postcentral parts of the cortex. Goldman-Rakic (1987) has argued that the prefrontal cortex is necessary for regulating behavior guided by representations or internalized models of reality. This part of the cortex is not required for behavior guided by external stimuli in the outside world. Therefore it seems relevant to find blood flow increases in that region during MSM. But the new finding that the cerebellum appears not only to be significantly involved both during motor performance but also during MSM (Decety and Philippon 1988; Decety et al. 1988a,b) will merit further studies in order to find out if the cerebellum is also involved in non-motor imagery of e.g. pure visual or auditive type. The cerebellar activation by motor imagery is congruent with the fact that there are anatomical connections between the SMA and the cerebellum, the basal ganglia and the ventral thalamic nuclei (Allen and Tsukahara 1974; Ito 1984). One could suggest that the activation of the cerebellum during MSM reflects an inhibitory mechanism which prevents the efferent impulses, triggered through imagery, to reach the medullar and muscle levels.

As suggested by Pickenhain (1984), mental simulation of motor behavior might trigger the motor program and involve all parts of the central nervous system which serve as subprogram effectors of the whole process of realization of a given action. Apparently this also includes autonomic mechanisms. However, it should be recalled that any outflow activity from the central nervous system also involves inhibitory processes. The formulation of a given motor plan, as well as the execution of it, requires rejection of irrelevant plans and concepts. Inhibition thus forms an important part of the general role played by the prefrontal cortex (Fuster 1980) in its simultaneous handling (selection/rejection) of temporally separate but mutually convergent serial action programs.

Our analysis of mental simulation of motor acts raises three questions:

- (1) Which components are actually represented in the motor programs triggered during mental simulation? A motor program is a part of the representation of an action. It is used to design the mental content related to the goal and/or the consequences of the action, as

well as the neural operations that are supposed to take place before an action begins (Jeannerod 1987). Mental simulation thus appears to involve both cognitive and motor processes, and it is difficult to separate the two.

(2) Which is the mechanism that triggers the motor program during motor ideation? It is obvious that this process is under voluntary control and thus deals with the complex and classical question of the nature of the free will. There is at present neither theoretical nor empirical information to clarify this question. Mental simulation forms a part of conscious-awareness. Hence, it is subject to capacity limitation (by motivation, interferences, etc.) and it is also energy and/or resource dependent, like all cognitive processes under voluntary control (Sanders 1983).

(3) Lastly, it seems important for further research to identify the inhibitory neural mechanisms which are responsible for the absence of a motor act during mental simulation of movements. The distribution of the cortical rCBF patterns during (1) mental simulation of movements and (2) actual movements, may give a clue. It appears that simulation activates only premotor and front regions, the basal ganglia and the cerebellum, while actual movement activates rolandic areas in addition. Thus the inhibitory process discussed here may prevent frontal processes from reaching the primary motor cortex. Studies of the cerebral metabolic activity and blood flow during simulation of motor behavior in normal subjects as well as in patients with cerebral motor disturbances may give some clarification of this crucial question.

Finally, it appears obvious that not only sport training may benefit from the study of mental simulation of movement. Indeed the clinical implications are numerous, especially for motor rehabilitation. It is possible that systematic mental simulation of motor behavior might be of particular value in facilitating motor recovery in situations where physical practice is difficult or painful or cannot be carried out. Functional rehabilitation following a lesion seems to include two processes which interact to maintain or restore an affected function (Jeannerod 1986). It has been suggested that the first process (restitution) expresses the tendency of the neural network to recover itself when interrupted. This process seems to be the consequence of biochemical events in the nervous tissue. Hence it is relatively independent of the environment. The second process (substitution) implies a func-

tional adaptation of the defective but partially restored network. This second process seems to depend strongly on external variables (sensory stimulation, physical therapy). Therefore, it lies close to hand to suggest that MSM should be of benefit during motor rehabilitation. In addition, such therapy might motivate the patient. The importance of motivation in a successful rehabilitation program appears well-accepted (Bach y Rita 1980). Indeed the reticulo-limbic system might be considered the major center of the brain that controls and regulates man's emotional tone, his abilities to lay down memories and retrieve them and his drive. One of the major goals in rehabilitation is to help the patient over a long enough period of time to restore his motivation. Such forms of therapy might benefit from information acquired in sport medicine, cognitive psychology as well as from neurophysiological studies presented in this review.

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