

Mini review

Action observation versus motor imagery in learning a complex motor task: A short review of literature and a kinematics study

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HIGHLIGHTS

- ▶ The mirror neuron system sub-serves both motor imagery and action observation.
- ▶ Both motor imagery and action observation play a role in motor learning.
- ▶ In this study we compared these strategies in learning a novel complex motor task.
- ▶ Action observation revealed better than motor imagery as a motor learning strategy.
- ▶ This is relevant in educational activities, sport training and neurorehabilitation.

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ABSTRACT

Both motor imagery and action observation have been shown to play a role in learning or re-learning complex motor tasks. According to a well accepted view they share a common neurophysiological basis in the mirror neuron system. Neurons within this system discharge when individuals perform a specific action and when they look at another individual performing the same or a motorically related action. In the present paper, after a short review of literature on the role of action observation and motor imagery in motor learning, we report the results of a kinematics study where we directly compared motor imagery and action observation in learning a novel complex motor task. This involved movement of the right hand and foot in the same angular direction (in-phase movement), while at the same time moving the left hand and foot in an opposite angular direction (anti-phase movement), all at a frequency of 1 Hz. Motor learning was assessed through kinematics recording of wrists and ankles. The results showed that action observation is better than motor imagery as a strategy for learning a novel complex motor task, at least in the fast early phase of motor learning. We forward that these results may have important implications in educational activities, sport training and neurorehabilitation.

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1. Introduction

This introduction includes two main parts: the first one is intended as a short review of literature on motor learning. Within the theoretical framework depicted in the first part, the second one outlines the background and aim of a kinematics study where the efficacy of two common strategies used to learn a novel motor task, motor imagery and action observation, has been directly compared.

Motor learning is the process through which we come to perform actions effortlessly after practice and interactions with the environment. By means of motor learning we continuously extend our motor repertoire.

Motor learning involves a number of interacting components [69]: processing and collecting sensory information relevant to action in an effective and efficient manner, applying a series of decision making strategies aimed at defining which movements to perform and which order to follow while performing them, activating control processes during motor performance including a feed-forward control, a reactive control and a biomechanical control.

Two experimental paradigms are usually used to study the mechanisms leading to learning new motor skills: motor sequence learning, assessing the incremental acquisition of movements in a

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specific behavior, and adaptation model, through which the capacity to compensate for changes in the environment is assessed [16].

For both paradigms distinct learning phases can be distinguished: a fast phase, in which improvement occurs within the very first training session; a consolidation phase, in which an improvement of performance occurs after at least 6 h from the first practice session; a slow phase in which further gains can be achieved across several training sessions; an automatic stage in which the motor task is performed automatically with poor cognitive demand; a retention state in which the motor performance can be executed in the absence of any practice after a long delay [16,31].

Two frameworks have been proposed so far describing the neural mechanisms underlying motor learning [13,16,35]. In one model [13] two parallel circuits operate in learning spatial and motor features of motor sequences. Learning spatial coordinates would be supported by a frontoparietal associative striatum-cerebellar circuit, while learning motor coordinates would be supported by a primary sensorimotor striatum-cerebellar circuit. In another model [16] it was proposed that during fast learning a cortico-striato-thalamo-cortical loop and a cortico-cerebello-thalamo-cortical loop are both recruited operating in parallel. Interactions between the two systems are believed to be crucial for establishing the motor routines necessary for learning new motor skills. When consolidation has occurred the motor representation of the learned motor skill is believed to be distributed both in the cortico-striatal loop and in the cortico-cerebellar loop, with a preeminent role of the cortico-striatal loop in the case of motor sequence learning and a preeminent role of cortico-cerebellar loop in the case of adaption learning. Little attention has been paid so far by current literature on motor learning to the best way to start a motor learning process and/or to the best way to gain a solid performance in a number of situations.

Two well assessed strategies for motor learning are action observation and motor imagery. Both action observation and motor imagery are believed to share the same neural mechanisms in the mirror neurons [38]. The discovery of mirror neurons [25,54], first identified in monkey premotor area F5, has revealed a mechanism in the brain which allows one to match an observed action with its motor counterpart in the observer's brain. In fact these neurons discharge when an animal performs an object-directed action and when the same, or a motorically related action, is performed by another individual.

Neurons endowed with mirror properties were found in both frontal and parietal areas, thus constituting the mirror neuron system (MNS) [19]. A system similar to the one described in the monkey has also been found in humans. A number of neurophysiological studies have shown that the observation of object-directed, as well as non object-directed actions, modulates the activity of those motor areas, normally involved in the actual execution of the observed actions, while brain imaging experiments have shown that during the observation of both object-directed and non object-directed actions different sectors of the premotor and parietal cortex are recruited [2,10,15,21,24,26,30,33,43,62]. In normal adults it has been shown that the activation of the MNS during action observation is related to the experience the observer has of the observed actions [3,8]. This seems to suggest that the development of the MNS runs in parallel with the motor experience of the observer. On the other hand classical studies do suggest that human newborns, only a few days old, are able to resonate with other adult individuals' actions [45], and infants less than two years old can predict other people's action goals [46] thus suggesting that the brain is endowed with a mechanism subserving a close coupling between action observation and execution from early development.

MNS has been involved in a number of motor as well as cognitive functions [19,34,55]. Several studies have consistently shown that action observation is an effective way to learn or enhance the

performance of that specific motor skill (observational learning) [for review see 66]. In a recent study participants who were required to perform a reaching task in a novel environment performed better after observing a video depicting a person learning to reach in the same novel environment as compared to participants who observed the same movements in a different environment [44]. In a pivotal study aimed at investigating the cortical mechanisms of human imitation, it has been found that areas involved in the actual execution of simple finger movements are crucially recruited also during the observation of identical movements made by another individual as compared to the presentation of spatial or symbolic cues [36]. Indeed during observational learning of complex actions, where mastering motor sequences not already in one's own motor repertoire is required, areas within the MNS have been found to be active from the observation of the model until its actual execution, with a specific contribution of prefrontal area 46 in reorganizing motor competences which are already part of our own motor repertoire in novel patterns fitting an observed model [4,65]. Moreover, using transcranial magnetic stimulation (TMS) it has been shown that the observation of another individual performing simple repetitive thumb movements leads to a kinematically specific memory trace of the observed movements in the motor cortex [60].

As for motor imagery, it has been defined as the ability to "mentally rehearse simple or complex motor acts that are not accompanied by overt body movements" [39]. That is, an individual imagines himself executing a particular action, almost perceiving the kinesthetic experience of the movement. This may be referred to as kinetic imagery. Imaging studies have shown activation of regions including supplementary motor area, superior and inferior parietal lobules, dorsal and ventral premotor cortices, pre-frontal areas, inferior frontal gyrus, superior temporal gyrus, primary motor cortex (M1), primary sensory cortex, secondary sensory area, insular cortex, anterior cingulate cortex, superior temporal gyrus, basal ganglia and cerebellum [14,20,28,32,43,53,57,59,61]. That is, motor imagery is associated with activity in a variety of regions, some of which have specifically been shown to be involved in action execution and action observation. It has been forwarded that the MNS is recruited whenever motor representations are recalled, and therefore not only during action observation, but also during motor imagery, dreams with a motor content and so on even in the absence of overt action [38]. Evidence for an improvement in motor performance after motor imagery has been collected in several studies. In an early study participants were requested to learn a five-finger exercise on a piano key-board over five days. Participants could either actually perform the motor task or practice it mentally (motor imagery). Using TMS it has been shown that the reorganization of the motor cortex following actual practice or motor imagery was similar [50]. In a kinematics study in which participants had to point with their right arm to different targets placed in the frontal plane, both physical and motor imagery training led to an improvement of performance as revealed by a decrease of movement duration and an increase of peak acceleration, respectively [27]. Similarly, in a finger tapping task both participants who received motor training and those receiving motor imagery improved significantly in motor performance [49].

Motor imagery has been suggested by some to be as effective as physical practice in improving motor performance, whereas others suggest this improvement should be more modest [37]. Improvement may also depend on the degree to which an action falls within one's repertoire [48].

While both action observation and motor imagery appear to result in improved performance, it is still an open question as to which of these is more effective as the two processes have never been directly compared in a complex task.

We addressed this issue with a kinematics study aimed at directly comparing the efficacy of motor imagery and action observation (observational learning) in learning a novel complex motor task. As a control condition we used a motorically neutral task. All participants had to learn a complex and unusual motor task which involved movement of the right hand and foot in the same angular direction (in-phase movement), while at the same time moving the left hand and foot in an opposite angular direction (anti-phase movement) all at a frequency of 1 Hz. Kinematics of wrists and ankles were recorded to assess motor learning. The study included only one practice session and therefore was aimed at assessing the role of both motor imagery and action observation only in the fast phase of a typical motor learning process.

2. Kinematics study

2.1. Materials and methods

2.1.1. Participants

Forty-five healthy participants (29 women and 16 men), recruited at the Vita-Salute San Raffaele University of Milan took part into the study. They all had neither history of orthopedic or neurological diseases affecting upper and/or lower limbs nor special motor competence (e.g., athletes, dancers, musicians). Participants gave written consent before taking part into the experimental procedure. The study was approved by the Ethical committee of the Scientific Institute San Raffaele, Milan.

Participants were randomly assigned to one of three groups, two experimental and one control group. Each experimental group underwent a specific training in order to learn a novel complex motor task: action observation (AO) or motor imagery (MI). The control group underwent a motorically neutral (MN) training. There were 15 participants per group (AO: 9 females, mean age 25 ± 3.96 years; MI: 9 females, mean age 23 ± 2.43 years; CO: 11 females, mean age 23 ± 1.53 years).

2.1.2. Experimental procedure

All participants had to learn a complex and unusual motor task which involved movement of the right hand and foot in the same angular direction (in-phase movement), while at the same time moving the left hand and foot in an opposite angular direction (anti-phase movement). The motor task had to be performed at 1 Hz for 30 s. The experimental procedure included three phases: pre-training phase, training phase and execution phase.

2.1.2.1. Pre-training phase. During this phase each participant sat alone on a comfortable chair in a quiet room. A sheet showing photos representing the motor task, and a written description of it, was presented to the participants for 90 s. The motor task had to be performed at a frequency of 1 Hz. In order to learn the frequency at which the motor task had to be performed, participants, after looking at photos and reading description of the motor task, listened to a beat of metronome paced at 1 Hz for 10 s. In the pre-training phase participants did not perform any movement. One of the experimenter (E.R.) checked that each participant had fully understood the task before entering the training phase. To this aim, participants were required to perform the shown action for a while. In case the motor task was not clear, the experimenter was allowed to demonstrate it for a short time.

2.1.2.2. Training phase. During this phase participants performed one of three training protocols (AO, MI, MN) for 7 min. During this period participants were instructed to avoid movements.

Participants in the AO group observed a movie in which both a man and a woman performed the motor task. To facilitate the comprehension of the task the video showed the action from four

different perspectives: right and left side, cranial and caudal side. Therefore the video included 8 sequences of equal length.

Participants in the MI group had to imagine themselves performing the motor task seen during the pre-training phase.

Participants in the MN group did not perform any specific motor training but were asked by an experimenter to solve some mental calculations.

2.1.2.3. Execution phase. At the end of the training phase the participants lay in a supine position on a bed. Before execution of the motor task the correct frequency of 1 Hz paced by a metronome was again demonstrated for 10 s. During the execution phase, participants had to execute the motor task continuously for 30 s. Participants were instructed not to cease execution of the task in the event of an error but to try to correct it and continue for 30 s.

2.1.3. Data acquisition and analysis

In order to assess the correct execution of the motor task by participants, wrists and ankles kinematics were recorded using an optoelectronic system composed of a six-video camera system (ELITE, BTS), after placing 12 passive markers, bilaterally, in the following positions: the lateral humerus condyle, the styloid ulnae and the head of the fifth metacarpus to reconstruct wrist kinematics, and the fibula head, the lateral malleolus and the head of the fifth metatarsus to reconstruct ankle kinematics. The sampling frequency was 100 Hz and the projection of the markers on the sagittal plane was considered, without accounting for out-of-plane movements. Wrist and ankle kinematics were shown using curves in which the movement range was reported on the y -axis and time on the x -axis. These curves were filtered using a fourth order Butterworth low-pass filter at a cut-off frequency of 6 Hz. Two experimenters analyzed the curves independently, by visual assessment, and identified the proportion of correct executions of the tasks. The two experimenters ignored the identity of the participant whose curves they were analyzing and the group he/she belonged to. The criteria used for the analysis of the curves were the direction of the four extremity kinematics, the range of motion of the four extremity kinematics (i.e., at least one third of the maximal excursion that each extremity reached in the specific task), and the delay among the four extremity kinematics (i.e., an extremity should not start the movement when another extremity had already finished its excursion). In case of disagreement, a third observer was consulted.

Finally, the following variables were measured using the Smart analyzer software: (1) duration of correct execution during the 30-s trial expressed as time of error; (2) mean frequency of wrist and ankle kinematics during the correct execution; (3) wrist and ankle mean range of motion during the correct execution; (4) discrete relative phase (AE \emptyset) between the peaks of the movement excursion reached by the first and the last of the four extremities, respectively, expressed as mean of the cycle by cycle AE \emptyset (Fig. 1).

The AE \emptyset was calculated as follows:

$$AE\emptyset_n = \frac{t_n^L - t_n^F}{t_{n+1}^F - t_n^F} \times 360,$$

where t_n^L and t_n^F are the times in which the first (F) and the last (L) among the four extremities, respectively, reached the peak of the excursion in the n th cycle [40,67].

Data was recorded using Biomech v1.5 software. The graphs for error time analysis were created using Smart analyzer v1.1. The discrete relative phase, the movement frequency and the range of motion of hands and feet were computed by Matlab v7.0 software.

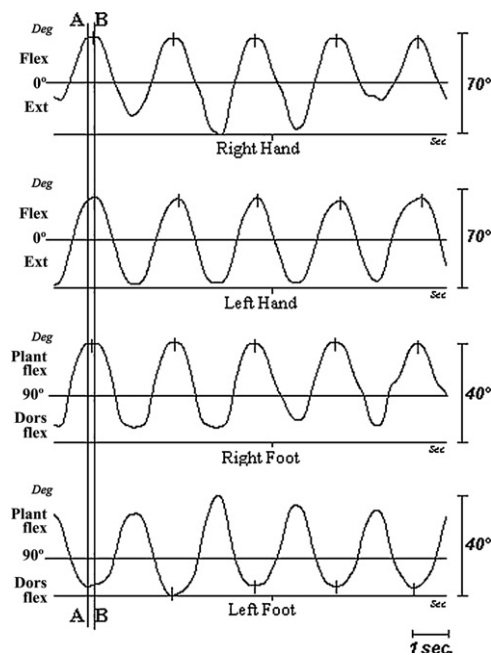


Fig. 1. The figure shows the angle tracks of the four limbs, in five movement cycles, when the subject performs cyclic homologous movements of the hands and alternating movements of the feet (HP condition). The right hand and foot movements have the same angular direction (RP condition) while the left hand and foot movements have opposite angular direction (LP condition). The x-axis represents the time, and the y-axis the movement excursion ($^{\circ}$). The cycle by cycle peaks of excursion are marked with vertical lines. The A and B vertical lines identify the time when the first limb (left foot, A) and the last limb (left hand, B) reach their respective peak of movement in the first cycle. The distance between these two lines represents the delay of synchronization, which was used to compute the discrete relative phase.

2.1.4. Statistical analysis

Data analysis was performed using SPSS v13.0 software. The three groups were compared using an ANOVA. A Bonferroni test was used as a post hoc analysis, when appropriate.

2.2. Results

Participants in the three groups were homogeneous for age and gender. Results are shown in Table 1.

2.2.1. Error time

Mean error time was 3.3 ± 7.6 s in the AO group, 20.1 ± 14.5 in the MI group and 16.9 ± 14.6 in the Control group. The comparison among the three groups, tested by ANOVA, showed a main effect of group ($F = 7.47$, $p = 0.002$). A Bonferroni test showed significant difference between both AO and MI groups ($p = 0.002$) and AO and CO groups ($p = 0.016$). No significant differences of error time were found between MI and CO groups.

Table 1

Main kinematics parameters in the three groups and corresponding p values (see Results for details).

	Action observation (AO)	Motor imagery (MI)	Control group (CO)	p
Error time	3.3 ± 7.6	20.1 ± 14.5	16.9 ± 14.6	0.002
Frequency right hand (Hz)	1.00 ± 0.00	0.93 ± 0.00	0.79 ± 0.27	0.008
Frequency right foot (Hz)	0.99 ± 0.00	0.94 ± 0.00	0.88 ± 0.14	0.011
Frequency left hand (Hz)	0.96 ± 0.00	0.97 ± 0.15	0.76 ± 0.27	0.009
Frequency left foot (Hz)	0.96 ± 0.00	0.94 ± 0.13	0.89 ± 0.18	NS
Range of motion right hand ($^{\circ}$)	58.0 ± 10.9	57.2 ± 11.3	59.5 ± 12.5	NS
Range of motion right foot ($^{\circ}$)	49.1 ± 10.3	45.4 ± 13.2	31.8 ± 12.9	0.002
Range of motion left hand ($^{\circ}$)	61.1 ± 7.0	51.9 ± 15.2	59.9 ± 17.7	NS
Range of motion left foot ($^{\circ}$)	39.9 ± 10.0	38.4 ± 17.2	25.4 ± 11.0	0.031
Discrete relative phase ($^{\circ}$)	20.9 ± 12.8	23.5 ± 12.1	29.6 ± 14.2	NS

2.2.2. Frequency

The mean movement frequency of the four limbs was 0.97 ± 0.00 Hz in the AO group, 0.94 ± 0.06 Hz in the MI group and 0.83 ± 0.21 in the Control group. The comparison among groups showed a main effect of group in the movement frequencies of the right wrist ($F = 5.41$, $p = 0.008$), right ankle ($F = 5.03$, $p = 0.011$), and left wrist ($F = 5.37$, $p = 0.009$). In these limbs the Bonferroni test showed significant differences in the AO and MI group compared to control group, in particular, in AO group for the frequencies of right wrist, right ankle and left wrist, while in MI group for the frequency of left wrist. There were no significant differences between AO group and MI group.

2.2.3. Range of motion

The mean range of motion for the two wrists and two ankles in the three groups was: $59.5 \pm 8.7^{\circ}$ and $44.5 \pm 10.1^{\circ}$ in the AO group, $54.5 \pm 13.6^{\circ}$ and $41.9 \pm 14.9^{\circ}$ in the MI group and $59.7 \pm 15.5^{\circ}$ and $28.6 \pm 11.1^{\circ}$ in the Control group. The comparison among groups regarding the range of motion of each segment showed significant differences in the right ($F = 7.15$, $p = 0.002$) and in the left ($F = 3.86$, $p = 0.031$) ankles.

2.2.4. Discrete relative phase

The means of the discrete relative phase were $20.9 \pm 12.8^{\circ}$, $23.5 \pm 12.1^{\circ}$, and $29.6 \pm 14.2^{\circ}$, respectively, for the AO, MI and control group. There was no significant main effect of group.

3. Discussion

The findings of our kinematics study clearly show that action observation is more effective than motor imagery (and, of course, than the control condition) in learning a novel, complex motor task. The results however were collected after one training session and therefore apply only to the fast phase of motor learning process. Both action observation and motor imagery most likely target the mirror neuron system, thus recruiting neural structures involved in the actual execution of the observed actions [38,47]. It is most likely, however, that through action observation MNS is triggered in a more ecological manner. In fact ventral premotor cortex receives visual inputs and therefore should be more excited by actual visual input than during voluntary recruitment in the absence of visual input and overt movement, as in the case of motor imagery [56]. Further, during action observation, as compared to motor imagery, the observer is provided with a model who performs the action correctly and in context; in contrast during motor imagery the individual has to rely completely on his own ability to rehearse or recruit the relevant motor representations and to perform covertly the action in a correct manner. In keeping with this there is evidence that learning through motor imagery is effective in subjects who are not completely novice, but less effective in completely naïve participants [48].

The results of this study are interesting because they show that action observation, most likely triggering the MNS, may be a useful

means of training in learning new motor tasks. We forward that this approach has the potential to be exploited in a variety of fields including educational activities, sport, and rehabilitation.

A number of studies have recently emphasized the fact that educational programs for both normally developing children and children with atypical development should be well grounded in neuroscience [29]. Learning by observation has been largely ignored in education and learning praxis and has been sometimes linked to “shallow, cheap and even fraudulent behaviour” [7]. The results of our kinematics study show that learning by observation is somehow the most physiological way to develop a novel motor competence, and should be exploited in a number of educational activities and in the acquisition of language. It is worth reminding that some classical authors in pedagogy and psychology [52,68] have stressed the role of motor experience and imitation to ensure a normal cognitive development. On the other hand, a number of studies have recently shown that in some developmental disorders, like autism, a hypofunction of the MNS [9,64] is evident, which in turn could explain some language and social disorders, most common in these children.

Motor imagery has been applied successfully to improve motor performance in sport training. The efficacy of motor imagery in sport practice, as an alternative or a complementary activity to motor execution, has been already shown by earlier studies [17,22]. More recently it has been reported that elite athletes practice motor imagery more than non competitive athletes [11]. Motor imagery has also been used to improve motor performance outside the sport domain. It has been shown that muscular force increased following motor imagery training [70] and that motor imagery improves musical performance like actual motor execution, although to a lesser degree [50]. Action observation, like motor imagery, has been shown to facilitate motor learning [44] and the building of a motor memory trace in normal adults [60]. To the best of our knowledge there are no controlled studies concerning the use of action observation as a method to improve motor performance in sport training. Since the findings of our kinematics study suggest that this practice may be even more effective than motor imagery in acquiring a novel motor task, studies in this field should be carried out.

The results presented here are also relevant to neurorehabilitation. Motor imagery has been applied for years as a tool in neurorehabilitation. Early studies showed an improvement of balance in elderly people through motor imagery [41]. More recently positive effects have been obtained in the recovery of stroke patients [6,42]. Motor imagery has also revealed a promising approach in Parkinson's disease (PD) [63] despite the fact that some brain imaging studies had shown an impaired capacity to imagine motorically in PD patients [12,23]. The findings of our study also strongly support the use of action observation treatment [58], recently proposed as an adjunct or an alternative to conventional physical therapy to promote recovery. During AOT, patients are required to carefully observe and soon afterwards execute different daily actions presented through video-clips. So far AOT has been successfully applied to chronic stroke patients [18], to the rehabilitation of lower limb functions in post surgical orthopedic patients [1], to the recovery of daily activities in PD patients [5] and to walking ability in PD patients with freezing of gait [51]. This approach may help patients in their daily activities since actions are trained in an ecological fashion and presented in the context of everyday life. Future studies should assess the possibility of combining motor imagery and action observation to fully capitalize on patients' recovery potential or define the conditions for which each is more appropriate.

In conclusion, a review of literature clearly indicates that both action observation and motor imagery may be useful strategies to learn a motor task and/or improve its performance. However these two strategies have never been directly compared to assess their

efficacy in learning a novel motor task. Our kinematics study shows a preeminent role of action observation as compared to motor imagery or a control condition in acquiring novel motor competence, at least in the early fast phase of a motor learning process. This may rely on a mirror mechanism subserving the capacity of the brain to couple an observed action with its motor counterpart in the observer's brain.

Action observation, as a physiological mechanism for motor learning, should be exploited in the future in educational activities, in sport training and neurorehabilitation more than it has been so far.

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