Exp Brain Res
DOI 10.1007/s00221-007-1086-x

RESEARCH ARTICLE

Visuo-motor learning with combination of different rates of motor imagery and physical practice

Nadia Allami · Yves Paulignan · Andrea Brovelli · Driss Boussaoud

Received: 13 September 2006 / Accepted: 24 July 2007

Abstract Sports psychology suggests that mental rehearsal facilitates physical practice in athletes and clinical rehabilitation attempts to use mental rehearsal to restore motor function in hemiplegic patients. Our aim was to examine whether mental rehearsal is equivalent to physical learning, and to determine the optimal proportions of real execution and rehearsal. Subjects were asked to grasp an object and insert it into an adapted slot. One group (G0) practiced the task only by physical execution (240 trials); three groups imagined performing the task in different rates of trials (25%, G25; 50%, G50; 75%, G75), and physically executed movements for the remaining trials; a fourth, control group imagined a visual rotation task in 75% of the trials and then performed the same motor task as the others groups. Movement time (MT) was compared for the first and last physical trials, together with other key trials, across groups. All groups learned, suggesting that mental rehearsal is equivalent to physical motor learning. More importantly, when subjects rehearsed the task for large numbers of trials (G50 and G75), the MT of the first executed trial was significantly shorter than the first executed trial in the physical group (G0), indicating that mental practice is better than no practice at all. Comparison of the first executed trial in G25, G50 and G75 with the corresponding trials in G0 (61, 121 and 181 trials), showed equivalence between mental and physical practice. At the end of training, the performance was much better with high rates of mental practice (G50/G75) compared to physical practice alone (G0), especially when the task was difficult. These findings confirm that mental rehearsal can be beneficial for motor learning and suggest that imagery might be used to supplement or partly replace physical practice in clinical rehabilitation.

Keywords Prehension · Mental rehearsal · Motor imagery · Learning

N. Allami · Y. Paulignan (✉)
Institut des Sciences Cognitives L2C2,
CNRS/Université de Lyon UMR5230,
67 bd pinel, 69675 Bron Cedex, France
e-mail: paulignan@isc.cnrs.fr

A. Brovelli · D. Boussaoud
Institut de Neurosciences Cognitives de la Méditerranée,
CNRS and Université Aix-Marseille, Marseille, France

Introduction

Motor imagery is defined as the process of mentally rehearsing a motor act without overt body movement (Jeannerod 1995). Several behavioral, brain imaging and clinical studies suggest that motor imagery and execution share similar behavioral and cerebral determinants. At the behavioral level, the duration of mentally simulated actions such as walking, writing or drawing is similar to the duration of their real execution (Decety and Michel 1989; Papaxanthis et al. 2002; see also for reviews Crammond 1997; Jeannerod and Frak 1999). Imagined and executed actions have been shown to obey the same biomechanical constraints, to share similar neuromuscular and cognitive mechanisms (Decety and Jeannerod 1995; Frak et al. 2001; Ozel et al. 2004; Papaxanthis et al. 2003), and to induce analogous physiological autonomic responses (e.g., respiration and heart rate; Decety et al. 1993). In parallel, brain imaging studies have shown that motor imagery induces similar electroencephalographic (EEG) patterns (Beisteiner et al. 1995; Caldara et al. 2004; McFarland et al. 2000; Romero et al. 2000) and activates a brain network that overlaps with that activated by real execution (Decety et al. 1994; Gerardin et al. 2000; Lafleur et al. 2002; Hanakawa et al. 2003; Jackson et al. 2003; Lacourse et al. 2004). In addition, transcranial magnetic stimulation (TMS) revealed that comparable changes in motor cortex excitability occur during motor imagery and execution (Fadiga et al. 1999; Hashimoto and Rothwell 1999).

Clinical studies have provided evidence that strengthens the idea that imagination and execution of a motor act rely on overlapping brain networks. Indeed, brain damage affecting execution of action also affects the ability to mentally simulate the action. In particular, patients with damage to the right parietal cortex are impaired in motor imagery and loose the capacity to predict the duration of a movement with mental simulation (Dankert et al. 2002; Sirigu et al. 1996). Furthermore, patients suffering from Parkinson's disease (caused by a dysfunction of basal ganglia and frontal cortex) have also been reported to have difficulties simulating mentally finger movement sequences or mental rotations of the hand (Dominey et al. 1995).

Taken together, these findings constitute strong experimental evidence supporting the functional equivalence hypothesis (Jeannerod 2001) between actual and imagined motor acts, which suggests that the two processes are interlaced and are mediated by similar brain networks. If motor execution and imagery are partially equivalent, the issue can be taken a step further by considering cognitive functions related to the motor system such as skill learning. This is a well-known phenomenon in professional sport practice, where physical training is often improved by mental simulation (Burhans et al. 1988). In clinical rehabilitation after damage to the central nervous system, the use of motor imagery has been recently reported to facilitate motor recovery after stroke (Jackson et al. 2001, 2004; Liu et al. 2004; Page et al. 2001), as previously proposed by several authors (e.g., Burhans et al. 1988; Hird et al. 1991; Porretta and Surburg 1995).

Several questions still need to be answered to improve our understanding of how motor imagery can be used in learning. In particular, what are the optimal conditions for the use of motor imagery to facilitate and improve learning? Similarly, to what extent can learning through motor imagery replace physical practice? To answer these questions, we designed a motor task where physical practice improves behavioral performance, with the idea that mental rehearsal of the same task would have equivalent behavioral benefits. The findings show that motor learning can occur through mental rehearsal alone, and that mental rehearsal for a large proportion of trials combined with a small rate of physical practice, leads to similar (or even better) performance than physical practice alone.

Methods

Experimental task

In pilot experiments, we used a simple grasping task, and found no improvement in performance after hundreds of trials. We thus designed a more complex task which consisted in a two-step sequence of movements, performed either physically or through mental rehearsal. The subjects were seated comfortably in front of a table, with the right hand resting palm down on the starting point located 29 cm on the right side of the sagittal axis. They were asked to grasp a plastic parallelepiped (first movement) and to insert it in a support (second movement, Fig. 1) as fast as possible. The object was located along the subject's sagittal axis at 38 cm from the chest. Half of object's surface was colored in gray, the other half was white with black marks which are matched in location with identical marks on the support. Subjects were instructed to grasp the object from its gray side and to place it carefully inside the support. To make the execution of the task more difficult, a marble was inserted in an unstable manner in a slight hole made on the object's surface. Furthermore, two small wooden sticks were glued on the object's small sides to force the subjects to grasp with a precision grip.

Behavioral paradigm and groups of subjects

Twenty-five volunteers participated in the study. The task was performed by real execution, or was mentally rehearsed. At the beginning of the session, all subjects executed physically

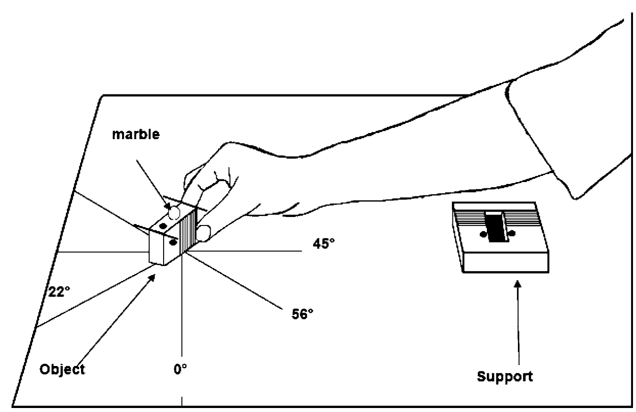


Fig. 1 Schematic representation of the task. A trial is accomplished in a sequence of two movements: the first movement consisted in reaching to and grasping the object with a precise grip (thumb and index only); the second movement consisted in taking the object to insert it into the support. The orientation of the support (0°) was the same throughout the trials, but the orientation of the object changed from trial to trial, in pseudo-random way (−22°, 0°, 45° and 56°). To make the execution of the task more difficult, a marble was inserted in a slight hole made on the object's surface. Furthermore, two small wooden sticks were glued on the object's small sides to force the subjects to grasp with a precision grip

five trials for familiarization with the task, with a single orientation of the object. In these trials, subjects learned how to place the fingers on the object's surface (a precision grip), and to adjust movement speed to successfully insert the object in the slot, without dropping the marble.

Physical execution

Before each trial subjects were told to close their eyes, allowing the experimenter to orient the object on the table surface. A tone was the signal to start the trial: subjects open their eyes, reach for and grasp the object with a precision grip (between thumb and index), transport it to the support and insert it correctly in the slot (i.e., the marks on the object must match those of the support; Fig. 1). Then the subject returned the hand to the starting position and closed the eyes, waiting for the next trial. The orientation of the object varied randomly from trial to trial. No feedback was given to the subjects about their performance.

Motor imagery

In this condition the subjects were instructed to follow the same sequence of events as in the real execution, except that they were told to imagine and feel themselves (first person) doing the task as if real (i.e., grasp the object, lift it and transport it to the support). When they completed the "mental" trial, they moved their right index finger, which was recorded as the end of the movement (see bellow).

Groups of subjects

Twenty-five right-handed subjects aged 20–37 years (average age, 28.5 years). All were naïve as to the purpose of the experiment or explicit knowledge concerning motor imagery processes. None of the participants had history of nervous or muscular disorders, and all gave their informed consent. The procedure was done in accordance with the French law (Livre I^{er} Titre I et II du Code de la Santé Publique).

The subjects were randomly included in five groups (of five subjects each), and each group was tested with a different combination of imagined versus executed trials. In one group (G0), the subjects performed the task by physical execution only, i.e., no imagination trials. This group allowed us to determine the average number of trials it takes to learn the task ($n = 240$). In the other groups, after the familiarization trials, the subjects first imagined doing the task for a number of trials, then performed physically to reach a total number of 240 trials. Thus, group G25 rehearsed the task in 60 trials (25% of the total number of trials) and executed 180 trials, G50 rehearsed in 120 trials (50%) and executed 120 trials, and finally G75 rehearsed in 180 trials (75%) and executed 60 trials. In a control group (GC), the subjects imagined a visual rotation task in the first 180 trials (75%) and then performed 60 trials of the same motor task as the other groups. In this latter group, the subjects were asked to imagine the rotation of a segment and to press a key when it is aligned with a tick mark on a circle. This condition was aimed to determine the effects of mental imagery that could be related to non-motor phenomena such as attention. In all the groups, each subject is tested in a single session of about 45 min of 240 trials. In the rare cases (1–4 trials per session) where subjects dropped the marble, the trials were excluded from the analysis.

Data acquisition and analysis

An Optotrak 3020 (Northern Digital Inc.) was used to record the spatial positions of an IRED marker taped on the styloid process of the wrist at a frequency of 200 Hz, and with a spatial resolution of 0.1 mm. For each trial, data acquisition started with the tone and lasted for 7 s. The data were analyzed off-line using Optodisp software (Marc Thevenet, Yves Paulignan, Claude Prablanc, copyright INSERM-CNRS-UCBL, 2001). The movement times (MT) were measured for each of the two movements separately on the basis of the wrist velocity profile (Fig. 2). Movement onset was defined as the time of the first of seven consecutive measures of increasing velocity amplitudes, whereas

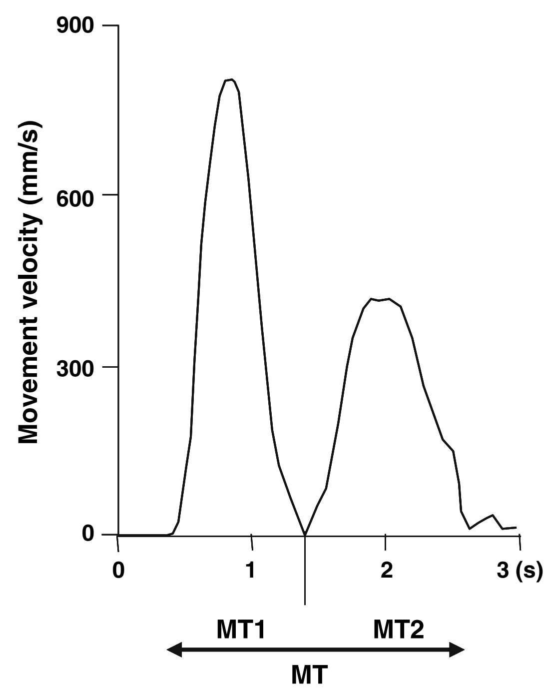


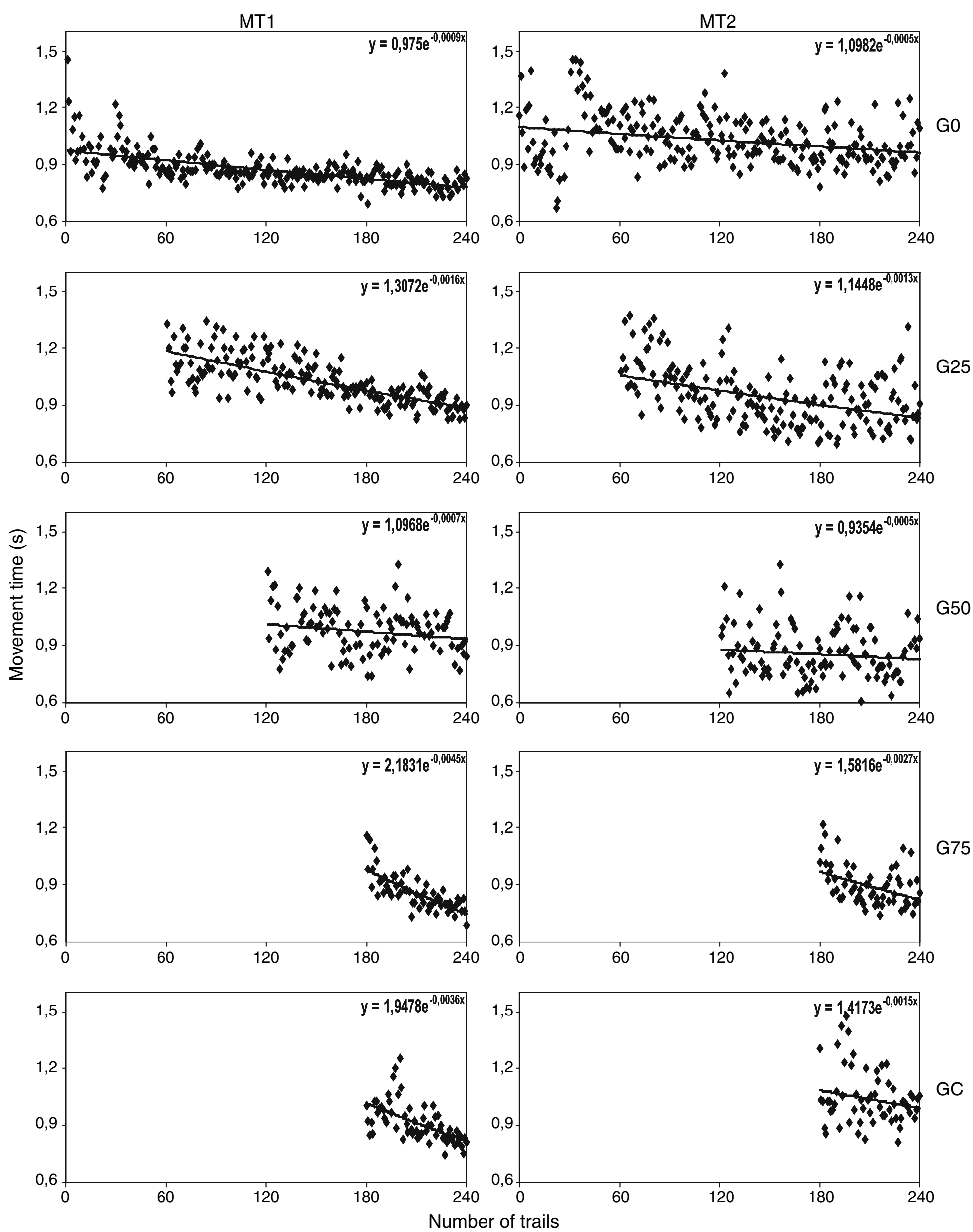
Fig. 2 Velocity of movement versus time. Movement onset was defined as the time of the first of seven consecutive measures of increasing velocity amplitudes, whereas the end of movement was defined as the null velocity. The first movement (MT1) corresponds to the reaching and grasping of the object. The second movement (MT2) corresponds to the transport of the object to insert it in the slot

the end of movement was defined as the null velocity. The first movement (MT1) is the reaching and grasping of the object (i.e., moving the hand from the starting point to the object). The second movement (MT2) corresponds to the transport of the object to insert it in the slot. The analysis was conducted on both the partial MTs (MT1 and MT2) and the total MT (MT = MT1 + MT2; see Fig. 2).

Statistical analysis

Due to randomization of object orientation, the same trial number (e.g., trial 61) does not necessarily correspond to the same orientation from one group to another. Thus, instead of using real data (which increases the variability), we computed MTs using a fitting equation. Movement times (MT1 and MT2) were plotted over the trials, and fitted with an exponential Logreg function on Microsoft Excel (Fig. 3). The fitting procedure produced learning curves for the two movements and for each subject. Finally, the equation of the fitted curve was used to calculate the MT for key trials in the learning session: the first executed movement (trials 1 for G0, 61 for G25, 121 for G50 and 181 for G75 and GC) and the last executed movement (trial 240). For group G0, we also calculated the movement at trial number 61, 121 and 181. We used Statistica workpackage (Statsoft) for data analysis. After having tested for normality of the values and homogeneity of variances across groups, an analysis of variance (ANOVA) was carried out to test differences between

Fig. 3 Individual measures of MT1 and MT2 for one subject of each group. *Lines* are the exponential fitting of the data with corresponding equation



groups and repeated-measures ANOVA was used to test for differences within groups. Then, post-hoc analyses (taking into account multiple comparisons) were conducted with LSD tests (Fisher Least Significant Difference method) and a $P < 0.05$ was chosen as the level of significance.

Results

General aspects

We have quantified learning by measuring the MT of the first and the last physical trials, and by comparing them across groups. In each group, the difference in MTs for the first and last trials indicates the improvement in performance with physical practice alone or after imagery (Fig. 4 for G0 and Fig. 5). Comparison of the first and last physical trials across groups revealed the gain in performance due to mental rehearsal. In particular, MT of the first executed trial (onset) across groups compares trials 1 in group G0, 61 in G25, 121 in G50 and 181 in G75.

The results are summarized in Table 1 and Fig. 5. The finding that the performance of the execution group (G0) improved with practice was a pre-requisite for searching for the effects of motor imagery. Testing homogeneity of variance showed that the variability of the data was similar among the different groups. We also compared the imagination time for the first trial (from the tone to the time reported by the subjects to indicate the end of the trial) across imagination groups, and found no significant effect [$F(6,30) = 0.46326$, $P = 0.82981$].

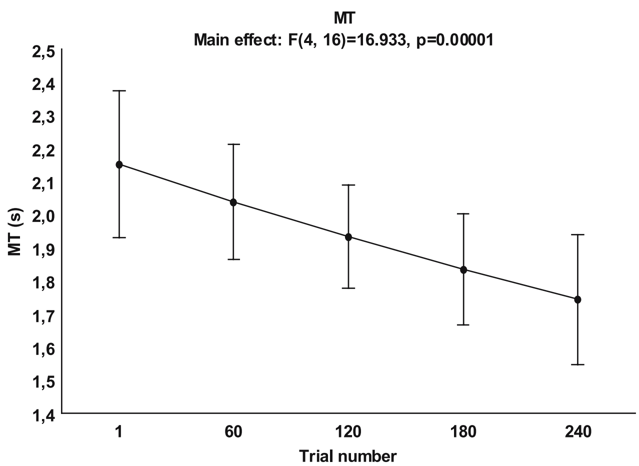


Fig. 4 Evolution of the performance in group G0 for total movement time for key trials

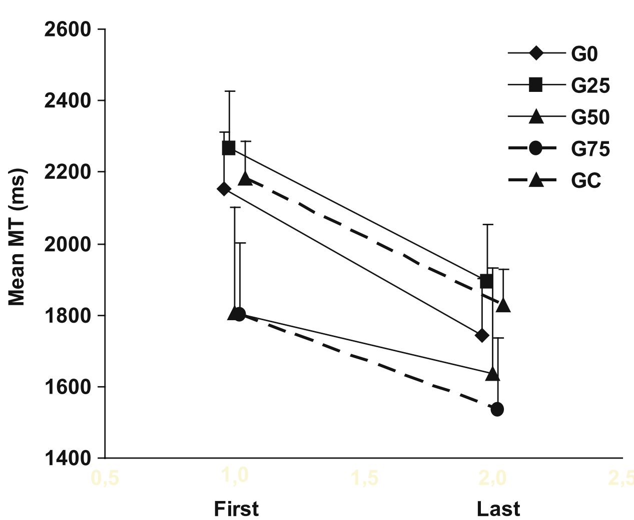


Fig. 5 Mean total movement times (MT) and SD for the first and last executed trials for each group

Effect of motor imagery

Effect on total MT (MT1 + MT2)

There was a strong group main effect on total MT [$F(4,20) = 6.3277$; $P < 0.0018$], indicating that the way the subjects learned the task (imagery vs. physical exercise) had a significant effect on total MT.

First trial The LSD post hoc analysis of the total MT of the first executed trial across groups (MT—first trial, Table 1, 2a) showed that the subjects in groups G50 and G75 were faster than the subjects in the other three groups (G0, G25 and GC). Indeed, the MT of the first executed trial for group G50 (performed after 120 imagined trials) and G75 (performed after 180 imagined trials) was approximately 350 ms shorter than the MT of the first trial executed by the subjects in group G0 (i.e., no imagination). The statistical analysis showed that the differences were highly significant (Table 2a). By contrast to groups G50 and G75, group G25 was not significantly different from G0.

Last trial Differences in MTs in groups G50 and G75 compared to group G0 did not reach significance. The only significant difference was between groups G75 and G25 (Table 2b).

Table 1 Movement times (MT, in ms) for the first and last executed trials in each experimental group, and Fischer LSD statistical *P* values

Group	MT—first	MT—last	*P* value
G0	2,153 (178)	1,744 (158)	0.00002
G25	2,267 (185)	1,895 (188)	0.00007
G50	1,807 (191)	1,636 (294)	0.033
G75	1,803 (143)	1,538 (198)	0.002
GC	2,184 (85)	1,828 (101)	0.00011

Table 2 Statistical analyses of MT (ms) across groups for the first (a) and last (b) executed trials

Group main effect $F(4,20) = 6.3277$; $P < 0.0018$		
	G50	G75
A LSD comparison—first		
G0	0.025	0.023
G25	0.0043	0.004
GC	0.016	0.015
B LSD comparison—last		
G0	0.46 (NS)	0.16 (NS)
G25	0.086 (NS)	0.02
GC	0.19 (NS)	0.056 (NS)

Therefore, the observed differences for the first executed trial between G50 and G75 relative to G0 did not lead to a gain in the performance at the end of the session. These results led us to analyze separately the MTs for the two movement components (MT1 and MT2).

Effect on MT1 versus MT2

There was a significant group effect on MT1 for the first trial [$F(4,20) = 3.92$, $P < 0.016$]. The LSD comparison for the first trial showed that G50 is only significantly different from G25 ($P < 0.017$), whereas G75 is different from G0, G25 and GC ($P = 0.029$, $P = 0.004$ and $P = 0.014$, respectively). For the last executed trial there was no group effect [$F(4,20) = 2.37$, $P = 0.087$]. This indicates that for the first movement, mental rehearsal brings little improvement to the performance.

There was also a highly significant group effect on MT2 for the first trial [$F(4, 20) = 11{,}240$, $P = 0.00006$], with important differences in MTs between groups G50 and G75 compared to groups G0 and G25 (Table 3; Fig. 6). For the last executed trial, MT2 was about 160 ms shorter in G50 and G75 than in group G0, and about 170 ms shorter compared to G25. The LSD comparison showed that MTs of G50 and G75 are significantly different from the other three groups (Table 3). Thus, mental rehearsal had a much greater benefit on the performance of the second component of movement than on the first one.

Comparison with the GC

Improved performance following mental rehearsal might be due to non-motor phenomena such as increased attention and/or concentration. If this were the case, any other imagination task would lead to similar improvements. The comparison between groups G50/G75 versus GC for MT2 showed significant differences (Table 3) for the first and last executed trials.

Discussion

The results reported in this study show that mental practice of a visuo-motor task is better than no practice at all. This is especially true for high rates of imagery (at least 50%), whereas the low rate of 25% was found to be ineffective. More importantly, we found that mental practice at high rates lead to similar performance as physical practice. In other words, mental rehearsal of 50 or 75% of the trials leads to a similar performance than actual execution of the same amount of trials. Finally, combination of imagery at high rates (50, 75%) with physical practice is sufficient to lead to similar (in some situations better) performance as physical practice alone. The control experiment suggests that the improvement in motor performance during mental rehearsal cannot be explained in terms of non-motor phenomena (namely attention), and that it likely involves sensorimotor learning processes. We will discuss these findings in light of the literature and in relation with the use of motor imagery in neurological rehabilitation.

Relation to previous studies

There have been numerous reports on the benefit brought by mental imagery to motor learning. Some studies have investigated the effect of mental rehearsal alone (Feltz and Landers 1983; Yue and Cole 1992; Yaguez et al. 1998; Jackson et al. 2001; Mulder et al. 2004; Ranganathan et al. 2004), while others have used different combinations of rehearsal and physical practice especially in clinical rehabilitation (Page et al. 2001; Gaggioli et al. 2004; Jackson et al. 2004). In general, imagery improves motor

Table 3 Analysis of MT2

Group	MT2—first (ms)	MT2 —last (ms)	LSD comp	G50		G75	
G0	1,117 (99)	929 (75)		First	Last	First	Last
G25	1,176 (127)	942 (126)	G0	0.0005	0.025	0.002	0.031
G50	871 (46)	763 (128)	G25	0.0005	0.016	0.0002	0.02
G75	908 (80)	770 (119)	GC	0.0003	0.034	0.001	0.043
GC	1,129 (95)	918 (76)					

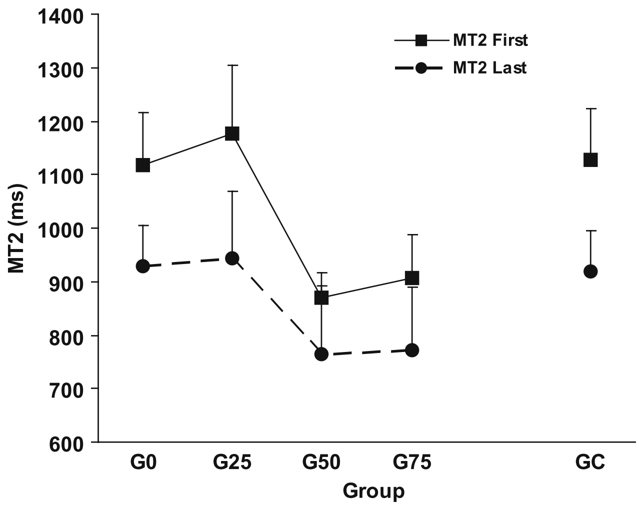


Fig. 6 Mean movement times of the second movement (MT2) and SD of all groups for the first (*squares*) and last (*circles*) executed trials separately

performance in a variety of tasks where different variables are measured including muscle contraction, movement speed and accuracy (Yaguez et al. 1998; Yue and Cole 1992; Ranganathan et al. 2004; Gentili et al. 2006). Among the studies that combined physical practice and imagery, some have used a low rate of imagery (e.g., Page et al. 2001; Jackson et al. 2004), while others used equal amounts of mental and physical practice (Gaggioli et al. 2004). Here, we varied the amount of training by mental versus physical practice in order to determine the optimal rate of imagery necessary for improvement of performance in a natural grasping task. Our main goal was to determine whether motor learning can take place by mental rehearsal, as previously shown, but more importantly to what extent can rehearsal supplement and/or replace physical practice. The findings clearly demonstrate, for the first time to our knowledge, that mental rehearsal of a motor task for a sufficiently long period has a better benefit in performance than physical practice. When subjects rehearse at least 50% of the total trials required to learn, the performance at the end of the training session is better compared to physical practice only. Even more interesting, the effect of mental rehearsal can be observed on the first executed trial, i.e., before even the subjects practiced physically. This important result suggests that mental rehearsal facilitates the brain networks involved in sensorimotor control, namely when large numbers of trials are used in the rehearsal period (more than 120 trials). This facilitation makes learning by physical practice more effective after imagery. In line with this finding, Pascual-Leone et al. (1995) reported that the level of performance, on a piano exercise, after 5 days of mental training was equivalent to that of physical practice after only 3 days. However, after adding only one physical training session to the 5 days of mental practice, subjects who practiced the task mentally reached the same level of performance as those who practiced physically.

Minimum required motor imagery for learning

Although we did not test a wide range of percentages of trials where subjects would rehearse the task, we were able to show that 60 trials of motor imagery are not enough to induce a learning effect for this task. Indeed, after imagination of the task in G25, the performance on the first executed trial, as well as that reached at the end of the training session did not differ significantly from the performance of the execution group (G0). Nevertheless, since the subjects of G25 reached the same performance as G0 with 60 trials less on physical practice, one might say that imagery at low rates has at least an equivalent effect to physical exercise. By contrast, mental rehearsal in 120 trials (50%) or more (i.e., 180 in our experiment) led to a significant improvement which could be measured on the first executed trial, as well as the last, specifically when the second movement (MT2). These results suggest that subjects need to rehearse mentally for a relatively large number of trials for learning to occur. More importantly, this study shows that mental rehearsal (for 120 trials or more) is sufficient alone to reach the same level of performance as that reached after 240 trials of physical practice (Table 1; Fig. 6).

Specificity of effect

It might be argued that non-motor phenomena, such as attention and/or concentration, could account for the improved performance after mental rehearsal (G50 and G75). This interpretation does not seem to hold true. Indeed, when subjects performed a visual rotation task through imagery in 75% of the trials, and then executed the same motor task as the other groups, there was no improvement in performance on the first executed trial. This was in strong contrast with the group that rehearsed the motor task in the same proportion of trials (G75), indicating that it is not sufficient to concentrate or focus attention while stimuli are presented for learning to take place. However, attention and/or concentration help improve the speed of learning by physical practice, as illustrated by the stiff drop of MT between the first and the last executed trials Nevertheless, the performance in the GC at the end of the training session does not differ significantly from that of physical practice alone. Overall, the findings suggest that rehearsal of a motor task is much more effective in improving the performance of that task than simple imagination of any task.

Task complexity and learning by motor imagery

Learning, i.e., the improvement of performance with practice, requires the task to be either unknown to the subject or more complex than the subject is used to. Because grasping is a major motor activity of our everyday life, one would expect that the performance has reached a near perfect performance and that there is little space for improvement in a simple laboratory experiment. Our pilot experiments confirm such an assertion. We thus made the task more complex by introducing a sequence of two movements, and constraints that made successful execution of the task difficult (difficult orientations of the object, an unstable ball on top of the object). These constraints required smooth and accurate movements. The group of subjects that practiced physically only (G0) confirms that, under these conditions, the performance improves and tends to reach a plateau within roughly 240 trials. The present findings show that the performance at the end of the training sessions was improved by mental rehearsal for the second movement. We suggest that this might be due to the higher level of difficulty in this second phase of the movement, which requires accurate and smooth transport of the object to end point. In a more general sense, these results suggest that motor learning would benefit more strongly from mental rehearsal in complex, difficult tasks than in simple ones.

Relevance to rehabilitation and sport psychology

Mental rehearsal has long been used in the field of sport psychology, and is known to optimize the performance in athletes, or help novices to learn new motor skills. In clinical neuropsychology, several studies have shown that mental practice can be successfully used to restore function in post-stroke hemiparesis (e.g., Dickstein et al. 2004; Gaggioli et al. 2004; Jackson et al. 2001, 2004; Page et al. 2001; Stevens and Stoykov 2003; Yoo et al. 2001). While in both fields of sport psychology and rehabilitation it is known that mental rehearsal cannot completely replace physical practice, the findings reported in this paper show how to better combine mental and physical practice to reach optimal results. First, mental rehearsal of any task (e.g., motor imagery) could be beneficial for motor learning or motor rehabilitation, especially in paralyzed patients who are unable to move their limb. Second, these behavioral findings further support the idea that mental practice can be a complementary clinical tool to current methods used in clinical rehabilitation. A pre-training session where subjects perform the motor task through imagery in a large number of trials would be expected to make learning or retrieval of motor performance through physical practice faster.

Potential limitations of the study

We would like to discuss one potential limitation of this study which concerns possible initial differences between groups, i.e., before training. Indeed, because our analysis focused on inter-group comparisons of the first and last executed trials, with relatively small size groups, the fact that the performance was improved after the imagery trials in groups G50 and G75 might be due to potential differences between groups before training. However, there is some evidence to overcome this limitation at least partly. First, not only that all groups were found to be homogeneous, but comparison of MTs of the first imagined trial across the four imagination groups did not show a significant difference. Second, although MTs in the imagination groups are generally longer that those of the GC G0, they did not differ significantly either. This is in line with previous studies showing that the time it takes to imagine doing a task is similar to the one it takes to actually do it (e.g., Frak et al. 2001). These pieces of evidence support our claim that the observed differences between groups G50 and G75 and the other groups are likely due to mental rehearsal, and not to initial differences in the performance. Nevertheless, with groups of five subjects, comparison with baseline performance before training would have been more convincing to rule out possible initial differences between groups. But this would have added physical practice trials before training and therefore affected the subsequent performance in the imagination groups. Indeed, a previous study by Jackson et al. (2004) showed that imagery after physical practice has little effect on performance.

Acknowledgments We are grateful to Pr. Marc Jeannerod, Drs. Martine Meunier and Richard Walker for their insightful comments and discussions. This work was supported by EU grant: IST programme (Project I-Learning, IST 2001-38861).

References

Beisteiner R, Hollinger P, Lindinger G, Lang W, Berthoz A (1995) Mental representations of movements. Brain potentials associated with imagination of hand movements. Electroencephalogr Clin Neurophysiol 96:183–193

Burhans RS, Richman CL, Bergey DB (1988) Mental imagery training: effects on running speed performance. Int J Sport Psychol 19:26–31

Caldara R, Deiber MP, Andrey C, Michel CM, Thut G, Hauert CA (2004) Actual and mental motor preparation and execution: a spatiotemporal ERP study. Exp Brain Res 159:389–399

Crammond DJ (1997) Motor imagery: never in your wildest dream. TINS 20(2):54–57

Dankert J, Ferber S, Doherty T, Steinmetz H, Nicolle D, Goodale MA (2002) Selective, non-lateralized impairement of motor imagery following right parietal damage. Neurocase 8:194–204

Decety J, Jeannerod M (1995) Mentally simulated movements in virtual reality: does Fitts's law hold in motor imagery? Behav Brain Res 72(1–2):127–134

Decety J, Michel F (1989) Comparative analysis of actual and mental movement times in two graphic tasks. Brain Cogn 11(1):87–97

Decety J, Jeannerod M, Durozard D, Baverel G (1993) Central activation of autonomic effectors during mental simulation of motor actions in man. J Physiol 461:549–563

Decety J, Perani D, Jeannerod M, Bettinardi V, Tadary B, Woods R, Mazziotta JC, Fazio F (1994) Mapping motor representations with positron emission tomography. Nature 371(6498):600–602

Dickstein R, Dunsky A, Marcovitz E (2004) Motor imagery for gait rehabilitation in post-stroke hemiparesis. Phys Ther 84(12):1167–1177

Dominey P, Decety J, Broussolle E, Chazot G, Jeannerod M (1995) Motor imagery of a lateralized sequential task is asymmetrically slowed in hemi-parkinsonien's patients. Neuropsychologia 33(6):727–741

Fadiga L, Buccino G, Craighero L, Fogassi L, Gallese V, Pavesi G (1999) Corticospinal excitability is specially modulated by motor imagery: a magnetic stimulation study. Neuropsychologia 37:147–158

Feltz DL, Landers DM (1983) The effects of mental practice on motor skill learning and performance: a meta-analysis. J Sport Psychol 5:25–57

Frak V, Paulignan Y, Jeannerod M (2001) Orientation of the opposition axis in mentally simulated grasping. Exp Brain Res 136:120–127

Gaggioli A, Morganti F, Walker R, Meneghini A, Alcaniz M, Lozano JA, Montesa J, Gil JA, Riva G (2004) Training with computer-supported motor imagery in post-stroke rehabilitation. Cyberpsychol Behav 7(3):327–332

Gentili R, Papaxanthis C, Pozzo DT (2006) Improvement and generalization of arm motror performance through motor imagery practice. Neuroscience 137:761–772

Gerardin E, Sirigu A, Lehericy S, Poline JBB, Gaymard B, Marsault C, Agid Y, Le Bihan D (2000) Partially overlapping neural networks for real and imagined hand movements. Cereb Cortex 10(11):1093–1104

Hanakawa T, Immisch I, Toma K, Dimyan MA, Van Gelderen P, Mark Hallett M (2003) Functional properties of brain areas associated with motor execution and imagery. J Neurophysiol 89:989–1002

Hashimoto R, Rothwell JC (1999) Dynamic changes in corticospinal excitability during motor imagery. Exp Brain Res Mar 125(1):75–81

Hird JS, Landers DM, Thomas JR, Horan JJ (1991) Physical practice is superior to mental practice in enhancing cognitive and motor task performance. J Sport Exerc Psychol 13:281–293

Jackson PL, Lafleur MF, Malouin F, Richards C, Doyon J (2001) Potential role of mental practice using motor imagery in neurologic rehabilitation. Arch Phys Med Rehabil 82(8):1133–1141

Jackson PL, Lafleur MF, Malouin F, Richards CL, Doyon J (2003) Functional cerebral reorganization following motor sequence learning through mental practice with motor imagery. Neuroimage 20(2):1171–1180

Jackson PL, Doyon J, Richards CL, Malouin F (2004) The efficacy of combined physical and mental practice in the learning of a foot-sequence task after stroke: a case report. Neurorehabil Neural Repair 18(2):106–111

Jeannerod M (1995) Mental imagery in the motor context. Neuropsychologia 33(11):1419–1432

Jeannerod M (2001) Neural simulation of action: a unifying mechanism for motor cognition. Neuroimage 14:S103–S109

Jeannerod M, Frak V (1999) Mental imaging of motor activity in humans. Curr Opin Neurobiol 9:735–739

Lacourse MG, Turner JA, Randolph-Orr E, Schandler SL, Cohen MJ (2004) Cerebral and cerebellar sensorimotor plasticity following motor imagery-based mental practice of a sequential movement. J Rehabil Res Dev 41(4):505–524

Lafleur MF, Jackson PL, Malouin F, Richards CL, Evans AC, Doyon J (2002) Motor learning produces parallel dynamic functional changes during the execution and imagination of sequential foot movements. Neuroimage 16(1):142–157

Liu KP, Chan CC, Lee TM, Hui-Chan CW (2004) Mental imagery for promoting relearning for people after stroke: a randomized controlled trial. Arch Phys Med Rehabil 85:1403–1408

McFarland DJ, Miner LA, Vaughan TM, Wolpaw JR (2000) Mu and beta rhythm topographies during motor imagery and actual movements. Brain Topogr 12(3):177–186

Mulder T, Zijlstra S, Zijlstra W, Hochstenbach J (2004) The role of motor imagery in learning a totally novel movement. Exp Brain Res 154:211–217

Ozel S, Larue J, Dosseville F (2004) Effect of arousal on internal clock speed in real action and mental imagery. Can J Exp Psychol 58(3):196–205

Page SJ, Levine P, Sisto SA, Johnston MV (2001) Mental practice combined with physical practice for upper-limb motor deficit in subacute stroke. Phys Ther 81(8):1455–1462

Papaxanthis C, Pozzo T, Skoura X, Chieppati M (2002) Does order and timing in performance of imagined and actual movements affect the motor imagery process? The duration of walking and writing task. Behav Brain Res 134:209–215

Papaxanthis C, Pozzo T, Kasprinski R, Berthoz A (2003) Comparison of actual and imagined execution of whole-body movements after a long exposure to microgravity. Neurosci Lett 339:41–44

Pascual-Leone A, Nguyet D, Cohen LG, Brasil-Neto JP, Cammarota A, Hallett M (1995) Modulation of muscle responses evoked by transcranial magnetic stimulation during the acquisition of new fine motor skills. J Neurophysiol 74:1037–1045

Porretta DL, Surburg PR (1995) Imagery and physical practice in the acquisition of gross motor timing of coincidence by adolescents with mild mental retardation. Percept Mot Skills 80(3 Pt 2):1171–1183

Ranganathan VH, Siemionow V, Liu JZ, Sahgal V, Yue GH (2004) From mental power to muscle power—gaining strength by using the mind. Neuropsychologia 42:944–956

Romero DH, Lacourse MG, Lawrence KE, Schandler S, Cohen MJ (2000) Event-related potentials as a function of movement parameter variations during motor imagery and isometric action. Behav Brain Res 117:83–96

Sirigu A, Duhamel JR, Cohen L, Pillon B, Dubois B, Agid Y (1996) The mental representation of hand movements after parietal cortex damage. Science 273(5281):1564–1568

Stevens JA, Stoykov MEP (2003) Using motor imagery in the rehabilitation of hemiparesis. Arch Phys Med Rehabil 84:1090–1092

Yaguez L, Nagel D, Hoffman H, Canavan AGM, Wist E, Homberg V (1998) A mental route to motor learning: improving trajectorial kinematics through imagery training. Behav Brain Res 90:95–106

Yoo E, Park E, Chung B (2001) Mental practice effect on line-tracing accuracy in persons with hemiparetic stroke: a preliminary study. Arch Phys Med Rehabil 82:1213–1218

Yue G, Cole KJ (1992) Strength increases from the motor program: comparison of training with maximal voluntary and imagined muscle contractions. J Neurophysiol 67(5):1114–1123