Research report

# Mentally simulated movements in virtual reality: does Fitts's law hold in motor imagery?

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## Abstract

This study was designed to investigate mentally simulated actions in a virtual reality environment. Naive human subjects ($n =$ 15) were instructed to imagine themselves walking in a three-dimensional virtual environment toward gates of different apparent widths placed at three different apparent distances. Each subject performed nine blocks of six trials in a randomised order. The response time (reaction time and mental walking time) was measured as the duration between an acoustic go signal and a motor signal produced by the subject. There was a combined effect on response time of both gate width and distance. Response time increased for decreasing apparent gate widths when the gate was placed at different distances. These results support the notion that mentally simulated actions are governed by central motor rules.

*Keywords:* Cognitive process; Response time; Motor imagery; Mental representation; Virtual environment; Human

## 1. Introduction

There is now considerable experimental proof that mental images can exhibit structural and functional characteristics that are similar to those of actual physical objects [18]. This functional equivalence not only concerns visual perception per se, but also visuomotor processes. Images of movements can affect the subsequent production of movements [6,7,16]. In blindfolded subjects required to walk towards previously inspected targets, imagery may be used to update an internal representation of the target location correctly [4,21].

Motor imagery can be defined as a dynamic state during which a subject mentally simulates a given action. Converging evidence from several sources indicates that motor imagery pertains to the same category of processes as those which are involved in programming and preparing actual actions, with the difference that in the latter case, execution would be blocked at some level of the cortico-spinal flow [15]. The hypothesis that motor imagery and motor preparation are both assigned to the same representational system is supported by several experiments using the mental chronometry paradigm. As early as in 1962, Landauer compared the time taken by a subject to say the alphabet or a series of number aloud and to think them to himself. He found that overt and implicit recitations took almost the same time [20]. Decety and Michel [3] reached the same conclusion in comparing actual and mental movement times in a graphic task. The time taken by right-handed subjects to write a short sentence was found to be the same whether the task was executed actually or mentally. The same temporal invariance was found, although movement duration was globally increased, when subjects used their left hand. Another interesting finding was that it took the subjects the same time, both actually and mentally, whether they wrote the text in large letters or in small letters. This behaviour conforms to the so-called 'isochrony principle' previously described for actually performed learned motor skills like writing or drawing [23,30]. Temporal correspondance between real and mentally simulated action has also recently been investigated by Parsons [24]. His findings indicate that the times for mentally simulating movements of one's hand from a natural resting posture into very many other postures are highly correlated with the time to actually make such movements and usually equal for the less awkward and more familiar target hand postures.

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Further results suggest that the similarity of duration for actually and mentally performed actions can be generalised beyond the category of learned skills. Decety et al. [4] compared the duration of walking at targets placed at different distances with that of mental simulation of walking at the same targets. Blindfolded subjects were asked either to walk, or to imagine themselves walking, at previously inspected targets located at 5, 10 or 15 m. Walking times were read on a stopwatch that the subjects held in their right hand, and that they switched on when they started to walk (actually or mentally) and off when they stopped. In the actual walking condition, walking times were found to increase with the distance covered. The same effect was observed in the mental walking condition. Moreover, and most importantly, mental walking times were found to be very similar to those measured in the actual walking condition for the same subjects and for corresponding distances. In another experiment [2], measurements were made in subjects required either to actually walk or imagine themselves walking on four beams that had the same length but varied in width. The beam width was assumed to be a factor of difficulty of the task, such that it would take longer to walk on a narrower beam. Indeed, a clear effect of the difficulty was found on both actual and mental walking times.

Georgopoulous and Massey [13] measured reaction time in subjects who were asked to move a manipulandum in a direction different from that indicated by a visual stimulus. The instruction was that they moved it at a given angle from the direction shown by the visual target. The duration of the reaction time increased with respect to the movements normally directed at the visual target. Furthermore, the increase in reaction time was a function of the amplitude of the angle. The authors interpreted this finding by making the hypothesis that subjects mentally rotated the movement vector until it reached the desired angle: hence, the increase in reaction time as a function of the angle. Georgopoulos and Massey interpreted their finding within the Fitts's law framework [8]. This law implies an inverse relationship between the difficulty of a movement and the speed with which it can be performed: increasing difficulty decreases the speed (i.e., increases the movement time). Reaction times, considered as mental movement time, were linearly correlated with mental movement difficulty (calculated from the amplitude of the angles) as classically found for the duration of executed movements. Hence their conclusion that, because Fitts's law hold in this condition, "both real and imagined movements might be governed by similar amplitude-accuracy relations". Neurophysiological support for this interpretation was obtained by Georgopoulos et al. [12] by transposing the same paradigm to monkeys trained to move a handle at given angles with respect to the direction of a target light. During the animal's performance, they recorded from neurons located within primary motor areas, coding for movements in a given direction. They computed the population vector (by summing the individual vectors encoded by several individual neurons) in relation to movements directed at visual targets, including in the condition where the monkey had to make movements in a direction different from that of the visual target. In the latter condition, they found that the direction of the population vector changed during the reaction time of the movement. The vector progressively rotated from the direction indicated by the visual target, to the direction of the intended movement. This finding substantiates the way parameters of movement execution (in this case, direction) are coded centrally during motor preparation, and provides a physiological rationale for the expression of such an universal motor rule as Fitts's law [8]. One should recall that Fitts' law has a high predictive value in various areas of motor performance [29]. For example, the speed-accuracy relationship holds for adults as well as children, in the foot, arm, hand and fingers movements; underwater and in the air [17]. It has, however, never been investigated in purely simulated actions.

The purpose of the present study was to verify the validity of Fitts's law in purely mental actions. A walking task was selected because it is an automatic activity and thus presumably less vulnerable to subjects' expectation. Its duration is long enough to be measured during mental simulation. In addition a similar paradigm has already been used in normal subjects to compare actual and mental walking time [2,4]. Normal subjects were instructed to walk mentally through a gate of a given apparent width positioned at different apparent distances. They had to indicate the times when they started walking, and when they had passed through the gate. Trials were repeated with gates of different widths. If the above predictions are correct, the mental walking time should correlate (at least within limits) with the gate width, the narrower and the more distant the gate, the longer the time. The main prediction was that: (1) the mental movement time should increase with decreasing gate' width for a given gate position and not only with respect to gate' distances; and (2) that the mathematical expression of this relationship (averaged movement time) should be linearly related to the $\log_2$ of the gate width.

## 2. Methods

### 2.1. Subjects

Sixteen right-handed and normally sighted subjects (8 females and 8 males) volunteered to participate in the experiment. Subjects were naive with respect to the aim of the study. Their age ranged between 20 and 35 years.

## 2.2. Apparatus

The experiment was designed on a Provision® virtual reality system (Division Ltd, Bristol, UK). The system consists of a transputer based parallel calculator that combines a 3D stereo image generator and 3D tracking and gestural devices (see Fig. 1). The user is immersed in a 3D virtual scene by the mean of a Virtual Technology® helmet carrying two LCD colour television screens equipped with wide angle optics. This dedicated parallel architecture allows real-time image rendering.

The image of a track was created in the visual environment. It consisted of a homogeneous surface limited by two lines converging with an apparent angle of 30° directed away from the viewer. Three gates of different width were generated by the calculator and displayed on the track at three different positions. Both the apparent distances between the positions and the apparent widths of the gates were incremented regularly, following an arithmetical law. The nearest gate position was displayed at a relative distance of 3 m from the subject's point of view, which corresponded to 100 virtual reality units (vr units). The second gate was displayed at 6 m (200 vr units) and the farest one at 9 m (300 vr units). The narrowest gate was displayed as it would be 45 cm width (15 vr units, the second 90 cm (30 vr units) and the third one 135 cm (45 vr units).The subjects right hand was equipped with a DataGlove® which was connected to the computer. This was used for recording motor signals produced by the subjects at the end of each trial.

## 2.3. Task and experimental procedure

Subjects were seated in a dental type chair with the headset fixed to their head. They wore the DataGlove®. They were first shown the track with three gates of the same width at the three possible positions. Then they were passively 'moved' along the track through the gates. This was repeated for the other gates widths. The purpose of this passive presentation was to demonstrate to the subjects that it was possible to walk through the virtual gates of different widths as if they were real. In order not to influence subjects's reports on mental duration, the rate of the passive moving was the same for the three gates' widths and very slow (15 s for each trial).

Subjects were then given general instructions and few test trial to become acquainted with the apparatus. To trigger the first trial, the subjects were told to clench their right fist (equipped with the DataGlove). Then they saw for 5 s one of the gates on the track, of which they were instructed to keep in mind the position and width. At the end of the visual exposure, the colour of the gate changed from blue to red. The subjects were informed that this was the preparatory signal instructing them to close their eyes, mentally visualise the previously presented target, and wait (1 s) for a sound acting as a go signal. The headset was then turned off and the sound appeared. At the go signal, subjects were required to imagine themselves walking-through the gate, and as soon as they passed through it, to open their right hand. The hand opening was taken as a signal for the completion of the mental walking task. A new gate was pre-
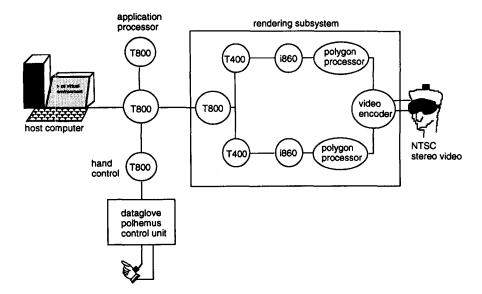


Fig. 1. A schematic representation of the transputer-based virtual reality system. The Provision® system consists of a number of parallel processing elements (the INMOS transputer) coupled to special purpose devices. The transputers are interconnected via the INMOS serial links and are dedicated to specific tasks: stereo video display, dataglove control, application process and direction of the operating system and host computer exchanges.

sented with an inter-trial interval of 1 s. Six trials for each of the gate's widths and the three positions were randomly presented. No instruction relative to the walking pace was given. Finally, subjects were told that if they missed a departure or an arrival during the mental task, they should tell the experimenter and so that the omitted trial would be replayed again. They could also stop the experiment whenever they wanted.

## 2.4. Data collection and analysis

Time measurements were collected by a personal computer connected to the transputer's calculator with a time resolution of 10 ms. The mean mental walking time as well as standard deviations were calculated for each subject using the Statistica® package on a Macintosh IIci. MANOVA and post hoc tests were then performed on group data. Regression coefficients were calculated on both individual and group data.

## 2.5. Post-experimental questionnaire

The subjects were kept naive about the aim of the experiment (i.e., the effect of target distance and width on response time). And a post-experimental questionnaire followed by structured interview was administrated in order to evaluate subject's tacit knowledge about the variables manipulated in the experiment.

After the experiment, subjects were given a questionnaire in which they were asked to answer two sets of questions.

In the first set, they were asked how they understood the relative distances/widths differed: "Do you think that the distance of the gates followed an arithmetical law? A geometrical law? A combination of the two? Or something else?" The same type of question was then asked about the gates's width.

Structured interviews were conducted after completion of the questionnaire to approach what the subjects experienced. These volunteered comments were followed by a specific inquiry about the two following points.

(1) Whether they were aware of the time they needed to perform the tasks and would this time be affected by the gates width and by the gates distance.

(2) Whether they imagined walking at their normal pace or differently.

Finally, in order to assess the degree of effort that they experienced during the completion of the experiment, the subjects were asked to rate their subjective sensation of effort by using a numerical scaling (1, no effort to 7, a lot of effort). This question was asked with respect to the gate distance as well as with respect of the gates width.

## 3. Results

One subject was excluded from the data computation from his comments during the interview. He indicated that he was not able to form a mental image of himself walking. Instead of using an imagery strategy, he counted his footsteps. He was thus aware of simulating walking with measured tread. For the first distance he counted 3 footsteps, 6 and 9 for the other distances wathever the gate width. His verbal report corresponded well to his response time.

## 3.1. Mental walking time

Mental walking time was found to increase with increasing gate distance and decreasing gate width (see Fig. 2). This effect was observed in all subjects. In addition, intrasubject variability increased with decreasing gate width, i.e., the narrower the gates the greater the variability. These observations are consistent with the speed-accuracy trade off, which implies an inverse relationship between the difficulty of a movement and the speed with which it can be performed [29]. Table 1
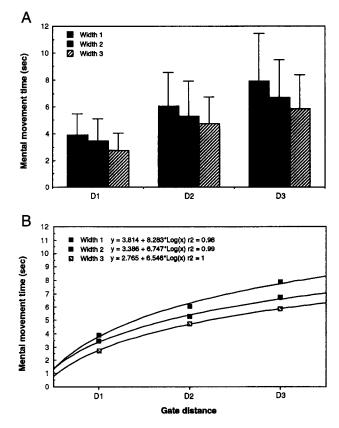


Fig. 2. Mean mental movement time (in s) of the 15 subjects. A shows the mean data as well as the standard deviation for the 9 conditions. B illustrates the increase in mental movement time with a logarithmical fitting for each width with respect to the target distance (D1, D2, D3). Bars represent standard deviations.

Table 1
Mean individual values of mental movement time (x) and standard deviations (sd) for the 9 conditions (D: distance, W: width). ●: missing value

| Subject | | D1W1 | D2W1 | D3W1 | D1W2 | D2W2 | D3W2 | D1W3 | D2W3 | D3W3 |
|---|---|---|---|---|---|---|---|---|---|---|
| S1 | x | 6.83 | 10.9 | 14.81 | 6.96 | 10.2 | 12.6 | 5.54 | 9.2 | 12 |
| | SD | 0.84 | 1.76 | 2 | 0.65 | 1.5 | 1.3 | 0.86 | 1.32 | 1.35 |
| S2 | x | 2.12 | 3.16 | 3.72 | 2.00 | 2.61 | 3.07 | 1.90 | 2.20 | 2.62 |
| | SD | 0.27 | 0.31 | 0.34 | 0.28 | 0.64 | 0.65 | 0.10 | 0.40 | 0.30 |
| S3 | x | 6.04 | 9.24 | 12.05 | 5.67 | 7.54 | 9.40 | 5.21 | 7.20 | 8.70 |
| | SD | 0.70 | 1.11 | 0.78 | 0.54 | 1.00 | 0.68 | 1.00 | 0.69 | 0.72 |
| S4 | x | 5.69 | 10.43 | 13.70 | 4.94 | 9.18 | 12.00 | 4.40 | 8.10 | 11.10 |
| | SD | 1.16 | 1.78 | 2.10 | 0.74 | 1.27 | 2.37 | 0.86 | 1.76 | 1.79 |
| S5 | x | 3.32 | 5.17 | 6.32 | 3.00 | 4.69 | 5.80 | 2.12 | 4.40 | 4.94 |
| | SD | 0.51 | 0.68 | 0.85 | 0.34 | 0.68 | 1.52 | 0.09 | 0.46 | 0.68 |
| S6 | x | 3.48 | 6.00 | 7.05 | 3.40 | 5.12 | 6.93 | 3.00 | ● | 5.80 |
| | SD | 0.45 | 0.55 | 1.10 | 0.42 | 0.73 | 0.86 | 0.24 | ● | 0.40 |
| S7 | x | 2.12 | 3.52 | 4.55 | 2.00 | 2.81 | 3.98 | 1.30 | 2.70 | 3.60 |
| | SD | 0.45 | 0.53 | 0.55 | 0.22 | 0.27 | 0.64 | 0.19 | 0.30 | 0.38 |
| S8 | x | 6.43 | 7.85 | 10.54 | 4.90 | 6.00 | 7.57 | 6.50 | 4.72 | 7.00 |
| | SD | 0.47 | 1.14 | 1.78 | 0.80 | 0.96 | 1.26 | 1.05 | 1.35 | 1.56 |
| S9 | x | 4.10 | 5.91 | 7.45 | 3.84 | 4.81 | 6.29 | 2.37 | 4.35 | 4.94 |
| | SD | 0.60 | 0.66 | 0.64 | 0.57 | 0.77 | 0.75 | 0.36 | 0.56 | 0.91 |
| S10 | x | 4.70 | 6.55 | 7.95 | 3.49 | 6.19 | 5.64 | 2.30 | 4.60 | 5.00 |
| | SD | 0.55 | 0.80 | 1.66 | 1.11 | 1.16 | 1.26 | 0.91 | 0.85 | 0.33 |
| S11 | x | 2.64 | 4.64 | 6.00 | 1.98 | 3.46 | 5.10 | 1.80 | 3.40 | 4.15 |
| | SD | 0.35 | 0.38 | 0.54 | 0.19 | 0.72 | 0.73 | 0.23 | 0.46 | 0.53 |
| S12 | x | 2.67 | 3.50 | 5.30 | 2.13 | 3.50 | 4.93 | 1.93 | 3.52 | 3.95 |
| | SD | 0.35 | 0.60 | 0.86 | 0.55 | 0.86 | 0.35 | 0.60 | 0.66 | 0.93 |
| S13 | x | 1.95 | 2.81 | 3.50 | 1.79 | 2.70 | 3.20 | 1.66 | 2.30 | 2.00 |
| | SD | 0.40 | 0.55 | 0.69 | 0.40 | 0.44 | 0.47 | 0.18 | 0.21 | 0.35 |
| S14 | x | 3.78 | 6.36 | 9.00 | 3.24 | 5.83 | 7.20 | 2.08 | 5.30 | 6.50 |
| | SD | 0.46 | 1.36 | 1.41 | 0.66 | 0.85 | 1.41 | 0.32 | 0.70 | 0.55 |
| S15 | x | 2.83 | 4.77 | 6.60 | 2.70 | 5.29 | 6.50 | 2.40 | 4.60 | 6.00 |
| | SD | 0.38 | 0.58 | 0.60 | 0.49 | 0.39 | 0.58 | 0.34 | 0.36 | 0.40 |

illustrates the mean values and standard deviations in all subjects.

Mean mental walking times were analysed in a MANOVA with gate distance and width as main factors. There were significant effects of distance, $F(2,26)=48.4$ $(P<0.001)$ and width, $F(2,26)=44.5$ $P<0.001)$, and a significant distance × width interaction, $F(4,52)=10.7$ $(P<0.001)$. Neuman-Keuls post hoc tests computed within each factor indicated significant differences between the three distances and between the three widths $(P<0.001$ in all cases). Fig. 2 illustrates the mean mental movement time according to the conditions.

In addition, the results were computed using the Fitts's law formalization [8]. This law relates Movement Time (MT) to the Index of difficulty ($I_d$) of the task:

$$I_d = \log_2 2D/W$$

where $D$ is target distance and $W$, target width.

Fitts's law is thus expressed as the relation

$$MT = a + b \log_2 2D/W$$

where $a$ and $b$ are two constants

Assuming that this law was valid also in our experimental conditions, virtual reality units (from the VR system) were attributed to the apparent distances of the
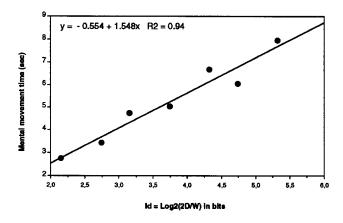


Fig. 3. Mental movement time plotted against the index of task difficulty ($I_d$) in 15 subjects. Least-squares regression line is shown. $I_d$ is calculated from the 9 original conditions. Since 3 values correspond to the same Id (1), they are averaged.

gates ($A=100$, 200, 300) and to their apparent width ($W=15$, 30, 45). Empirical values of MT were found to correlate with the estimated Id, as follows:

$$MT = -0.554 + 1.548 I_d \quad (r^2=0.94).$$

The Fig. 3 illustrates this relation on group data.

Individual values for the equation are presented in Table 3.

### 3.2. Post-experimental questionnaire and debriefing

All subjects but one reported that the target position followed an arithmetical law.

Most subjects reported that more effort was required when then imagined walking towards a distant gate as compared to the first one (see Fig. 4). Nonparametric Wilcoxon tests were applied for the differences in subjective sense of effort related to the gate distances (i.e., between D1 and D2, and between D2 and D3). All $T$ were significant for gate distance, $P < 0.002$. The same nonparametric analysis was applied for the sense of effort related to the gate width (i.e., between W1 and W2, and between W2 and W3). In that case there were no significant differences in the subjective sense of effort for gate width. Interestingly there is a dissociation between the target distance and the target width for the sense of effort. The subjective sense of effort increased with gate distance but was not significantly affected by

Table 2
Individual values of the equation $MT = a + b \log_2 2D/W$

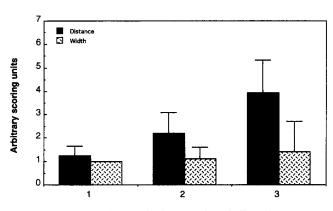| Subject | $b\, y$ (slope) | $ax$ | $r^2$ | $P$ level $<$ |
|---------|-----------------|--------|-------|---------------|
| 1 | 2.773 | −0.466 | 0.90 | 0.001 |
| 2 | 0.590 | 0.435 | 0.95 | 0.0001 |
| 3 | 2.084 | 0.201 | 0.90 | 0.0009 |
| 4 | 2.919 | −2.010 | 0.91 | 0.0007 |
| 5 | 1.251 | −0.228 | 0.90 | 0.001 |
| 6 | 1.372 | −0.066 | 0.90 | 0.003 |
| 7 | 0.960 | −0.611 | 0.93 | 0.0004 |
| 8 | 2.046 | −1.140 | 0.94 | 0.0002 |
| 9 | 1.460 | −0.481 | 0.94 | 0.0002 |
| 10 | 1.638 | −1 | 0.97 | 0.0001 |
| 11 | 1.337 | −1.234 | 0.92 | 0.005 |
| 12 | 0.977 | −0.124 | 0.76 | 0.01 |
| 13 | 0.578 | 0.335 | 0.88 | 0.001 |
| 14 | 1.971 | −1.858 | 0.91 | 0.0007 |
| 15 | 1.275 | −0.155 | 0.78 | 0.008 |



Fig. 4. Mean rating of the subjective sensation of effort. Bars represent standard deviations.

gates widths. Therefore, one can hardly suppose that the effect of gate width on the mental movement time is due to a related sensation of effort. It also suggest the implausibility of the use of tacit knowledge. In addition, the subjects didn't know, or were not aware, that gate width would affect mental walking time.

Finally, the reports of the subjects indicated that they were all able to form a mental image of themselves walking at their own pace, not particularly thinking about the speed. None of them could have predicted that the width of the gates influenced the mental walking time.

### 4. Discussion

An indirect approach to investigate motor cognitive processes that are involved in mentally simulated movement may be provided by applying the mental chronometry paradigm to situations in which one can predict that task duration is affected, as it is for actual performance, by central motor rules such as the speed-accuracy trade off. Virtual reality represents a new opportunity to carry out such paradigms.

The present study was designed to test the hypothesis that Fitts's law holds in motor imagery. Our results showed that the time needed to imagine oneself walking towards a given gate is affected both by its distance and its width. In accordance with Fitts's law, we found that when the mental movement time is plotted versus the index of difficulty ($I_d$) of the task, the increase in movement time is a linear function of Id.

The use of tacit knowledge has often been claimed to explain results in situations of mental imagery such as mental rotation tasks [26]. According to some authors [14], such paradigms are vulnerable to demand characteristics induced by the experimental situations, the subject's training and knowledge of the world, and the experimenter's knowledge of the hypotheses. In the case of our study, subjects could have mimicked imagined performance in terms of actual performance and thus ensure similar performance parameters. The fact that all subjects but one reported that the target distance followed an arithmetical law, suggests that they were aware during the experiment that the difference between gate 1 and gate 2 was the same than the one between gate 2 and gate 3. If they had used this tacit knowledge to compute the time, one should have found an increase in mental duration in the same proportion between gates of the same width. Clearly, this was not the case. Fig. 2 shows the mean raw group data, before any computation. If the subjects had used their tacit knowledge, the increase in mental movement time should fit a linear regression and not a polynomial one as it is the case (see Fig. 2B). Interestingly, the subject excluded from the computation because counting his footsteps exhibited a

linear increase in mental movement time between gate position 1 and 2, and between 2 and 3 with no effect of gate width.

The issue of performance equivalence between perceptual and imaginal systems has been addressed by several investigators [21,25]. The two systems have performance equivalence to the extent that they produce comparable time scores for a given task. But time score may be equivalent without underlying processes being identical. To postulate that the two systems have process equivalence to the extent that the same underlying processes are involved, neurophysiological data are desirable to obtain more decisive evidence. In this context, the fact that our results are consistent with those of Georgopoulos and Massey [12,13], suggesting that imagined movements are governed by similar amplitude-accuracy relationships as for real movements is of special interest.

Physiological evidence for this interpretation is also provided by regional cerebral blood flow measurements in human during mental representation of action. Roland and collaborators [27] 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 (SMA). Their results thus confirmed that the SMA plays an important role for the internal programming and simulation of complex motor sequences. Measuring rCBF with $^{133}$Xe and a gamma camera, Decety et al. [5] 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 SMA, and also the cerebellum were significantly activated. The participation of the cerebellum has been confirmed recently with tomographic methods [28,1]. The above-mentioned cortical as well as sub-cortical areas found to be activated during motor imagery pertains to the neural network known to be involved in the early stage of motor control. This further supports the argument about common neural mechanisms of imagery and motor planning.

Another interesting result in this experiment is the sensation of effort that was reported by the subjects that may be taken as an evidence of central processing. Such sensation are reported to occur prior to EMG onset in subjects instructed to perform a movement at will [22]. Complete paralysis in patients following pyramidal lesions at the cortical level or neuromuscular blockade experimentally induced in healthy subjects is not accompanied by sensation of effort when attempting to move [9,10]. But the sensation reappears during partial recovery of movements when neural traffic is re-established. Gandevia et al. [11] suggested that the discharge responsible for these sensations do not arise directly from the corticospinal pathways because transcranial electrical stimulation of this pathway does not produce a sensation of effort but the sensation of a passive movement. Thus, as suggested by Gandevia [10], the relevant discharges for the sensation arise from structures such as the premotor cortex and basal ganglia, which subsequently impinge upon primary motor cortex and the descending pathways. Our results conform to the view that the sensation of effort reflects the amount of muscular force programmed by the central system for the distance to be covered. Indeed, The subjects subjective sensation correlates with the gate distance but not with the gate width. The effect of gate width on mental movement time cannot be attributed to computation of force, but presumably to a tradeoff between movement amplitude and accuracy.

Finally, our results support the notion that motor imagery involves not only a perceptual memory system, as it has long been suggested [16] but also has temporal characteristics that appear to be specific to motor output. They further suggest that the process that produces motor imagery is the same process that is used in actual motor control. Mental imagery shares mechanisms with more basic processes used in like-modality perception, memory, and motor control [19].

## Acknowledgment

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