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The timing of mentally represented actions

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The performance of subjects walking blindly to previously inspected visual targets (located at 5, 10 or 15 m from the subjects) was studied in 2 experiments. In Expt. 1, subjects selected as good visual imagers were instructed to build up a mental representation of the target. Then they had to either actually walk or imagine themselves walking to the target. Walking time was measured in both the actual and the mental performance. It was found that subjects took almost exactly the same time in the two conditions. Accuracy of these subjects was also measured in the actual walking task. They were found to make no direction errors and to slightly overshoot target location. Subjects from another, control, group, who received no instructions about visual imagery made much larger errors. In Expt. 2, actual and mental walking times were measured in the same subjects as in Expt. 1, while they carried a 25-kg weight on their shoulders. In this condition, actual walking time was the same as in Expt. 1, although mental walking time was found to increase systematically by about 30%. These results are discussed in terms of the neural parameters encoded in the motor program for actually executing or mentally performing an action.

INTRODUCTION

A number of psychophysical experiments have revealed that visual images of objects seem to be represented as perceptual analogues which preserve the metric spatial properties of the represented objects. Shepard and Metzler first showed that represented 3-dimensional shapes are mentally manipulated in the same way as if they were real 3-dimensional objects; the time taken to mentally rotate such shapes increases linearly with the angle of rotation[19]. Similarly, Kosslyn et al.[13] showed that the time required to scan across visual mental images increases linearly with the distance to be scanned (see also refs. 17, 21).

These results suggest that processes underlying mental movements within visually represented space might be similar to those underlying actual movements within physical space. Support of this idea is provided by experimental data on reaction times. The concept that the length of time that precedes movement execution 'often reflects the complexity of decisions required to select and prepare the necessary voluntary response' (ref. 12, p. 55) is now widely admitted. Accordingly, in a recent experiment, Georgopoulos and Massey[6] requested subjects to perform reaching movements at various angles from a stimulus direction and found that reaction times of these movements increased linearly with the size of the angle. They proposed that this increase in reaction time was related to mentally rotating the movement vector until the angle of rotation corresponded to the size required. In both the Shepard and Metzler[19] and the Georgopoulos and Massey[6] experiments, the linear relationship

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between duration of the postulated mental rotation and the size of the angle of rotation is remindful of the classical relation between movement time and task 'difficulty' observed during execution of real movements[3,15]. This similarity suggested to Georgopoulos and Massey that both real and imagined motions might be governed by the same principles in the amplitude–accuracy domain.

The hypothesis that the timing of mental actions would in fact reflect 'motor' constraints on the represented tasks has at least one logical consequence. Namely, that the time taken to travel mentally between objects represented on a spatial map should be in one way or another related to the time taken to actually travel between objects in physical space. In the present experiments we undertook a direct comparison of the timing of movements actually performed with that of movements mentally represented by the same subjects, who were requested either to walk, or to imagine themselves walking, to previously inspected targets.

EXPERIMENT 1

Methods

Subjects. The subjects in this experiment were 20 right-handed male and female University students in Physical Education (age, 20–27 years). They were randomly split into two groups of 10. Subjects from the first group received specific instructions (see below) for using a mental imagery strategy during the experiments (imagery group, IG). Subjects from the second group were naive in this respect and did not receive any instruction concerning imagery (no-imagery group, NIG).

Apparatus and procedure. The experiment was conducted on a running track (width: 1.20 m) in an outdoor stadium. Three white marks (30 by 20 cm), traced on the ground with white chalk, were used as targets. The targets were located 5 m apart from each other. Subject's starting position on the track was such that his/her distance from the targets could be either 5, 10 or 15 m. Starting position was varied from trial to trial.

At the beginning of each trial, IG subjects were placed on the track. They were then allowed to look for 5 s at one of the targets. After being blindfolded they were instructed to construct a mental representation of the track and the target. Finally, after another 5-s delay, they were requested either to walk at a normal pace to the target and to stop when they thought they had reached its location (actual walking condition), or to imagine themselves walking to and stopping at the target (mental walking condition). Ten trials were performed in each of the two conditions and for each of the 3 target distances (60 trials per subject). Conditions and target distances were randomly distributed in order to avoid block effects.

The same procedure was followed with NIG subjects, except that they received no instruction about imagery and were only requested to perform the actual walking condition.

Two types of measurements were made: (1) Accuracy of reaching the targets was measured in the actual walking condition. The directional error was measured as the angle in degrees between the actual direction of the middle of the target and the direction defined by the endpoint of the subject's trajectory. However, an error was scored only when the subject's trajectory ended outside the target surface (errors to the right were scored with a + sign, errors to the left, with a −); The distance error was measured as the difference (in centimeters) between the final position of the subject (measured at the subject's ankle axis) and the target position (hypermetric errors were scored with a + sign, hypometric errors with a −). (2) Walking time (in seconds) was measured in both the actual and the mental walking conditions. Subjects held an electronic stopwatch in their right hand. They switched the stopwatch on when they started to walk (actually or mentally) and off when they stopped. Walking time was read directly by the experimenter on the stopwatch. Subjects were given no information on their spatial or temporal errors.

Imagery testing in subjects of the IG group. Three different tests were applied to IG subjects prior to the experimental sessions for evaluating their imagery ability, the Sheehan[18] Mental Imagery

Questionnaire, the Hall et al.[8] Movement Imagery Questionnaire, and the Gordon[7,16] Test of Visual Imagery Control. All subjects scored as good imagers. Finally, another questionnaire[1] was administered after termination of the experiment, in order to check subjects' tacit knowledge about mental imagery. In response to the relevant questions in this questionnaire, all subjects rejected the idea that visual imagery might produce effects on motor learning.

Results

Accuracy. A striking difference in accuracy appeared between the two groups. IG subjects tended to walk to the target in the middle of the track and no direction errors were scored for any of the 3 target locations. Distance errors were of a small amplitude. As a rule, subjects tended to slightly overshoot target position (Table I).

By contrast, NIG subjects made large direction errors. They erred systematically to the right of the targets, and the size of the error increased with target distance (Table I). Distance errors were also consistently larger. Subjects overshot the position of targets located at 5 m, and undershot the position of more remote targets (Table I).

Walking time: IG subjects. In the actual walking condition, walking time varied across subjects (between 3.8 and 7.2 s for targets at 5 m, between 6.9 and 12.9 s for targets at 10 m, and between 10.8 and 19.3 s for targets at 15 m). However, in each individual subject, walking time increased with the distance covered (Fig. 1).

In the mental walking condition, walking times were very close to those measured in the actual walking condition for the same subjects and for the corresponding targets. The similarity of the two distributions of walking times was confirmed statistically. An intra-subject paired t-test showed non-significant differences between the means of the two distributions. T_9 ranged between 0.2 and 1.1 for 5 m; 0.2 and 1.3 for 10 m; 0.3 and 1.7 for 15 m, $P > 0.5$. In addition, the mean values of travel time for the actual and the mental walking conditions were plotted against each other for each target. Intra-subject linear correlation coefficients ranged between $r = 0.89$ and $r = 0.99$. Fig. 2 shows the linear aspect of the distribution.

A two-way inter-subject analysis of variance was conducted on walking times × distance (5, 10, 15 m) × modality (actual, mental). No difference was found between actual and mental walking times ($F_{1,54} = 0.02, P > 0.5$); there was a significant difference between the 3 distances ($F_{2,54} = 131.7$, $P < 0.001$). No interaction was significant ($F_{2,54} = 0.2$, $P > 0.5$).

Walking time: NIG subjects. Walking times in the actual walking condition in NIG subjects were in the same range as in IG subjects for the corresponding targets. However, the scatter of the values around the mean was much larger in NIG

TABLE I

Constant error (CE) and variable error (VE)

+, overshooting; −, undershooting of target position. Errors in direction are in degrees of arc.

	Target distance					
	5 m		*10 m*		*15 m*	
	CE	*VE*	*CE*	*VE*	*CE*	*VE*
IG						
Distance (cm)	+ 15.3	0.67	+ 13.3	8.7	+ 13.2	11.7
NIG						
Distance (cm)	+ 13.0	44.1	− 78.2	34.6	− 122.6	32.2
Direction (degrees of arc)	2	3	4	2	7	6

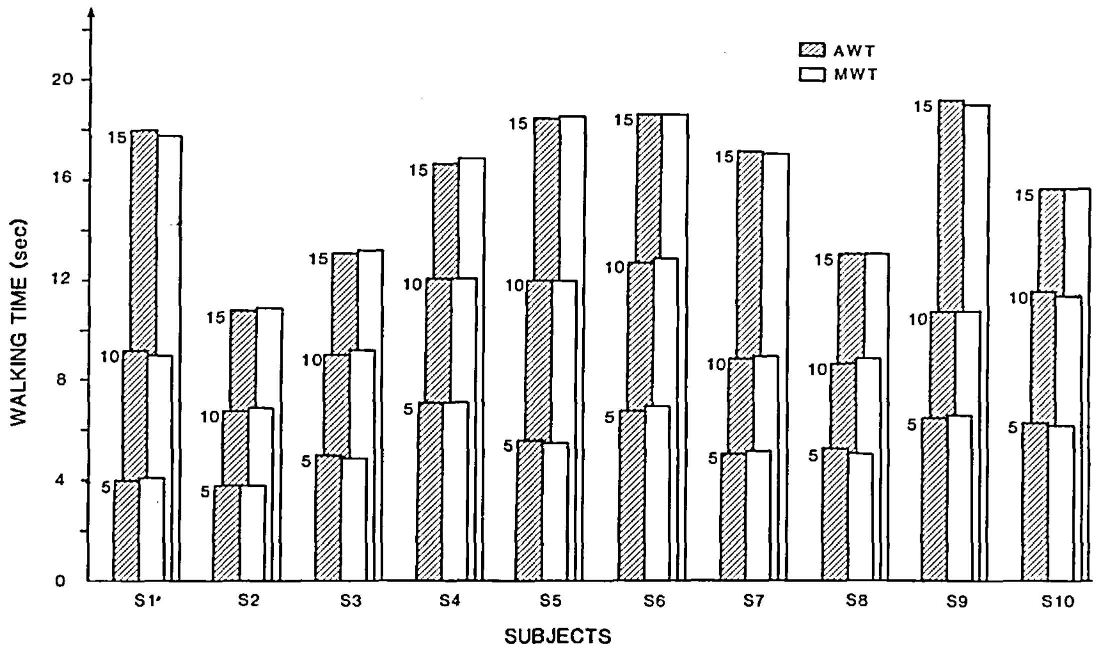

Fig. 1. Mean walking time (in s) for the 10 IG subjects (S1–S10) of Expt. 1. AWT, actual walking time; MWT, mental walking time. Values at top of histograms: distance of targets (5, 10, 15 m).

subjects (mean 5.77, S.D. 1.95 for 5 m; mean 9.79, S.D. 2.52 for 10 m; mean 13.82, S.D. 5.77 for 15 m). The comparison of IG/NIG subjects for walking times was non-significant ($F_{1,54} = 0.40$, $P < 0.5$).

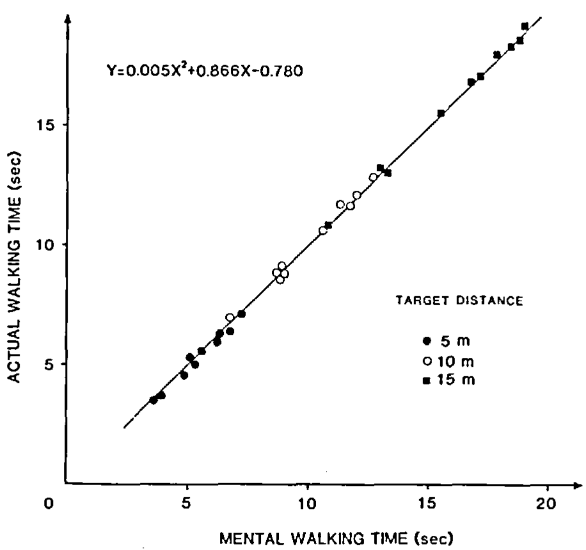

Fig. 2. Intrasubject distribution of mean mental walking times plotted against mean actual walking times in the 10 IG subjects of Expt. 1.

Discussion

(1) Although these were not of primary concern in this experiment, the accuracy data are worth discussing first. Our walking condition was similar to the situation used by Thomson. This author (see ref. 20) observed that subjects walking blindly to a previously seen target made larger errors when the target distance exceeded about 10 m. Thomson attributed these larger errors to the decay of spatial memory for target position during the time spent walking to the target: hence, the more distant the target to be reached, the longer the travel time and the greater the error. Indeed, when Thomson's subjects were asked to wait before they started to walk, their error rate increased proportionally, even for close targets. The critical time was found to be in the range of 8 s. Our results in NIG subjects show that distance error increased faster than target distance, and that larger errors appeared when the time spent between target exposure and subject's arrest near the target exceeded some 15 s. Interestingly, this was not the case for IG subjects performing the actual walking task with an imaging strategy, who made little or no error whatever distance to

the target or time to reach to it. The present results therefore only partly replicate Thomson's data. In addition, Thomson[20] reported an increase in error variability, not in amount of error (for another non-replication, see ref. 2).

The important point here seems to be that subjects in whom the use of an imaginal representation of target locations was reinforced were more accurate than subjects performing normally, an effect which reminds the well-known beneficial effect of mental practice in learning motor skills (e.g. ref. 11). This suggests that imagery can partly substitute for visual input, at least for distances not exceeding 15 m. It would be interesting to determine how far the use of an internal representation would accurately guide locomotion and prevent the otherwise rapid decay of spatial memory. Indeed, the role of visual imagery in short-term retention of movement end location was examined by Housner and Hoffman[9]. They compared performance of subjects with extreme scores on the space relations of the Differential Aptitude Test. Their findings suggested that visual imagery may be an important factor in the retention of location, but of little functional significance in the recall of distance.

(2) The main result to be considered in Expt. 1 is in fact the similar increase in walking time with target distance, in both the actual and the mental walking conditions. Increase in mental walking time with target distance replicates and expands the findings of Kosslyn et al.[13] for the distance of visual scanning. However, the fact that walking time was invariant *across* actual and mental conditions raises an interesting question: is temporal invariance due to a strategy of replicating in the mental condition the temporal sequence registered in the actual condition; or is it related to the fact that the mechanism which is said to compute mental time is the same as the mechanism which is used for preparing the actual movement? And if so, which parameter(s) of the motor 'program' are used during mental execution of the task?

One way to answer this question is to introduce an external constraint on the motor task. It was conjectured that such a constraint should not affect in the same way actual and mental performance, because the constraint would exert its effect only during execution of the actual movement. Therefore, and somewhat paradoxically, if the mechanisms used in the mental and the actual conditions were to be the same, the subjective representation of the movement should differ from its actual appearance. It was also conjectured that this difference might possibly affect the estimation of movement duration. The previous experiment was thus repeated in the same subjects in a condition involving an external constraint, namely the subjects were requested to actually walk or to imagine themselves walking to the targets, while carrying a heavy load on their shoulders.

EXPERIMENT 2

Method

Subjects. The ten subjects from the IG group in Expt. 1 were used in this experiment, which was carried out several weeks after completion of Expt. 1.

Apparatus. The same running track with the 3 targets was used as in Expt. 1.

Procedure. A 25-kg weight was placed on subjects' shoulders in a rucksack. Subjects were placed on the track and were instructed to look at one of the targets for 5 s. Then they were blindfolded and were requested either to walk and reach the target location (actual walking condition) or to imagine themselves walking to it (mental walking condition).

Each subject received 10 trials for each of the 3 target distances in each of the two conditions (60 trials per subject). Trials were randomly alternated in order to avoid block effects. Walking time was measured as in Expt. 1.

Results

Walking time. Walking times in the actual walking condition with the 25-kg load were in the same range as those measured in the same subjects in Expt. 1 (actual walking condition; paired t-test, $P > 0.5$, n.s.). By contrast, travel times in the mental walking condition with the load were significantly increased in all subjects and for all target distances (paired t-test, t_9 ranging between 6.9 and 7.2 for 5 m; 8.3 and 9.6 for 10 m; 6.5 and

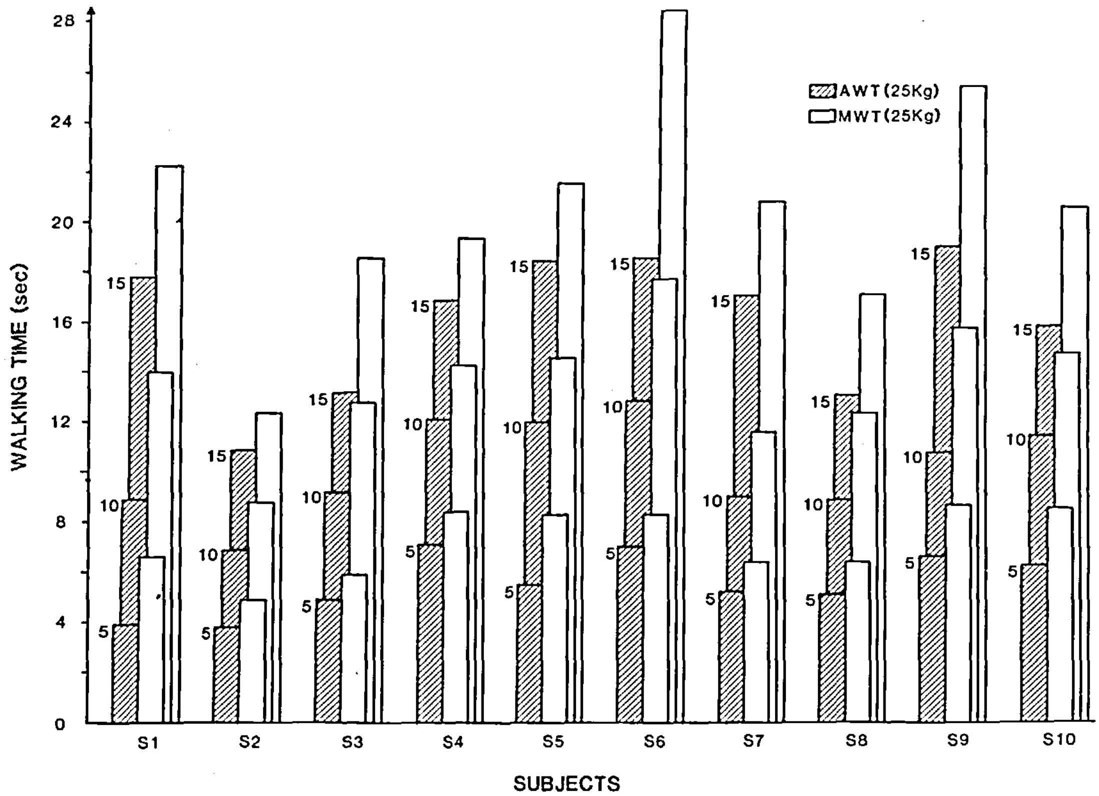

Fig. 3. Mean walking time (in s) for the 10 subjects (S1–S10) of Expt. 2. Subjects carried a 25-kg load on their shoulders. AWT, actual walking time; MWT, mental walking time. Values at top of histograms: distance of targets (5, 10, 15 m)

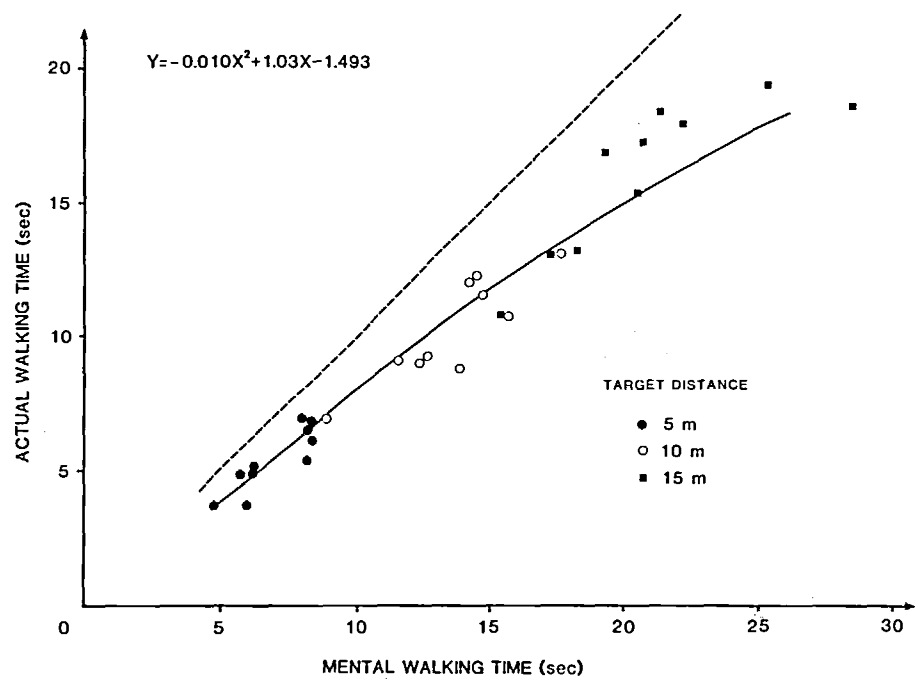

Fig. 4. Intrasubject distribution of mean mental walking times plotted against mean actual walking times in the 10 subjects of Expt. 2. The solid line represents the fitting curve for this distribution. The dashed line reproduces the regression line calculated for the same subjects in Expt. 1 (see Fig. 2).

6.9 for 15 m, $P < 0.001$; Fig. 3). This increase was not linear across distances. The distribution of actual walking times vs mental walking times for the 3 target distances fitted a polynomial equation (Fig. 4). This distribution was clearly different from that observed in Expt. 1.

The intra-subject variability was relatively small both in the actual and the mental conditions. In the actual condition, coefficients of variation ranged between 1.4% and 6.3% for 5-m targets, 3.4% and 9.2% for 10-m targets, 2.8% and 4.4% for 15-m targets. In the mental condition, coefficients of variation ranged between 2.8% and 10% for 5-m targets, 2.6% and 6% for 10-m targets, 1.2% and 11% for 15-m targets.

A two-way inter-subject analysis of variance was conducted by using walking time data in the mental conditions from Expts. 1 and 2, on load conditions (with or without 25-kg load) × target distances (5, 10, 15 m). There was a significant difference between the two load conditions ($F_{1,54} = 23.4$, $P < 0.001$). In addition significant differences were found between distances ($F_{2,54} = 104.7$, $P < 0.001$). No interaction was found between those two factors, $P > 0.5$.

Subjective report. Subjects spontaneously reported in the mental walking condition a strong sensation of effort which they felt to increase with the distance of targets.

Discussion

As predicted, the results from Expt. 2 demonstrate a clear dissociation between actual and mental walking times, such that the subjects carrying a 25-kg load imagined themselves taking longer to walk to the targets than it actually took to perform the task. Because actual walking times with the load remained virtually the same as without the load (as shown by comparing data from the same subjects in Expts. 1 and 2), the difference between actual and mental times was due entirely to an increase in mental times.

GENERAL DISCUSSION

The main issue to be discussed at this point is two-fold: first, what is the basis for the mental estimate of duration of an imagined action? And second, how does this estimate relate to the mechanisms subserving actual execution? In the conditions of Expt. 1, the time needed for performing a task mentally was the same as that needed for actually executing the same task. This result suggests that there would be no discontinuity between mechanisms responsible for mental performance and those for physical execution. The current model accounting for this mental to physical continuity (see refs. 10, 14) implies that the executive movement structures are subordinate in the hierarchy to mental structures which represent the concepts underlying any preplanned action sequence. The content of the mental structures should logically be the same whether the executive structures are activated or not. The results obtained in the load condition (Expt. 2), however, are in apparent discrepancy with this model. In this condition, the mental walking times were found to be significantly longer than the actual walking times.

This result first validates the ensemble of results obtained in the two experiments reported in this paper. The fact that the similarity of actual and mental walking times obtained in Expt. 1 could be broken down in Expt. 2 demonstrates that subjects were not merely replicating in the mental walking task the duration they had experienced in the actual walking task. The following explanation can be proposed for this difference. One has to consider that when subjects carried the load, they generated centrally a greater force to overcome the resistance produced by the load. In the actual walking task this increase in force resulted in maintaining the same speed as without load. By contrast, in the mental walking task the increase in encoded force was not used to overcome the resistance due to the load, and was interpreted as an increase in duration of the action.

The exaggerated sensation of effort reported by subjects in the mental walking task during Expt. 2 may also be considered under the light of the above discussion. Feelings of intense effort are frequently reported by subjects attempting to move partially paralysed limbs, either in pathological conditions[4] or following local curarization. Gandevia and McCloskey[5], in an attempt to objectify these sensations, used the curarization technique for measuring the quantity of effort that subjects have to make in achieving a given task with partially paralyzed limbs. They asked subjects to press a lever with one thumb in order to produce a reference tension, displayed visually on an oscilloscope screen. With the other thumb, the subjects had to press another lever so as to match the muscular effort produced by the 'reference' thumb. During partial curarization on the side of the reference thumb, the subjects indicated with their other (non-paralysed) thumb, a much larger muscular effort than normally required to produce the same tension. The exaggerated sensation of effort reported by our subjects in the present experiment may thus also be interpreted as a subjective correlate of the increased effort specified by the program in order to overcome the weight.

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