

On Information Processing and Performing a Movement Sequence*

J. T. Massey, A. B. Schwartz, and A. P. Georgopoulos

Philip Bard Laboratories of Neurophysiology, Department of Neuroscience,
The Johns Hopkins University, Baltimore, MD 21205, USA

INTRODUCTION

This paper deals with two main questions. First, is it possible to appreciably increase the speed of the movement without degrading its accuracy? Or, according to the information-theoretical formulation of Fitts (1954), is it possible to increase the information transmission capacity of the motor system? In a way, of course, this characterizes skilled motor performance. For example, a good tennis player is frequently both fast and accurate, especially so if one considers that the accuracy required under these circumstances extends to several aspects of movement, i.e., orientation of the hand, force of hitting the ball, precise timing, etc. How is that increase in information processing being accomplished? We suggest that a key factor responsible for the improved performance in skills that involve sequence of movements may be a simultaneity of motor processing. It seems that, under certain conditions, generating a movement *while* another movement is evolving or being generated "primes" the perceptual-motor system so that, instead of being constrained it actually processes information more efficiently and emits movements that are faster than, and as accurate as, movements produced in isolation. We examined some of these questions in the experiments that we describe below.

The second question deals with the explanation of the sequential movement pattern that we observed in this experiment. In particular, we tested the idea that the two-movement trajectory observed in our experiments could have been the outcome of a superposition of two movement plans. (The idea was pointed to one of us (A.P.G.) by P. Morasso during this meeting.) Assuming that each movement plan is specified in kinematic terms (Morasso 1981), we identified two plans plausibly dictated by the stimulus configuration. Representative estimates of velocity traces were obtained from within the experiment, and were superposed according to the experimental condition and algebraically summed. The resulting profile was then compared to that observed. We found that the observed profiles deviated systematically from those predicted.

These results led us to a close examination of the dynamic aspects of the movements in the task. A detailed analysis of the force patterns applied by the subjects during these movements revealed that both monkey and human subjects followed a more or less stereotyped strategy in performing the task. This strategy simplified decision making and minimized calculations in the task, although at

* This research was supported by US Public Health Service grants NS17413, NS07226, and MH18030, which we gratefully acknowledge.

the expense of physical work, and ensured that subjects would achieve the behavioral goal of capturing the target as soon as possible.

METHODS

The behavioral apparatus consisted of a 25 cm x 25 cm planar working surface (tilted 15° from the horizontal in a direction toward the subject) and a light weight, low friction articulated manipulandum. The device has been described in detail previously (Georgopoulos et al. 1981). The subject grasped the distal end of the manipulandum and captured within a 10 mm diameter transparent plexiglass circle attached to it, a lighted red light emitting diode (LED) on the working surface. Three male rhesus monkeys (3.5 - 5 kg) were trained for approx. 1 month in a reaction time, LED capturing task (see Georgopoulos et al. 1981) before performing in the task of the present study. Three men performed 20 trials in that same task before performing the task described below.

The present task was as follows. A trial started after a 2 s intertrial interval (lights off) by turning on a LED at the center of the working surface. The subject captured it, and waited there for a 1 to 3 s variable period of time (center hold time), after which that LED was turned off as another one was turned on at either a 12 or a 6 o'clock position, each 8 cm away from the center. The LED (first target) stayed on at that position for a time (interstimulus interval, ISI) and then was turned off while another one (second target) was turned on at the symmetrically opposite position, at 6 or 12 o'clock, respectively. The monkey was rewarded by a drop of juice when he captured this last LED. The instruction to the human subjects was "to capture the LED that is on as soon as possible". If the subject moved out of the center hold area (a circle 10 mm in diameter) within the first 100 ms after the onset of the first target, the trial was labeled "early reaction time error"; if he did not move after 700 ms had elapsed, it was a "late reaction time error"; if the hand did not arrive at the target area (a 25-mm diameter circle centered on the target) within 1500 ms after he started moving, it was a "movement time error"; finally, if the subject did not hold within the final target area for at least 250 ms, the trial was labeled "target hold error".

ISI was 50, 100, 150, 200, 250, 300, and 400 ms in different trials. The probabilities of occurrence of task events were balanced, so that the subject could not predict the position (12 or 6 o'clock) of the first target LED ($p = 1/2$), whether that target would shift position or stay on as in a control trial ($p = 1/2$), or, in the case of target shift, the time of the shift ($p = 1/7$). Ten to fifteen successful target shift trials were performed by each subject. Control (nontarget shift) trials were seven times as numerous because of the balanced probabilities in the task described above.

The experiment was controlled using a PDP11 laboratory minicomputer. The position of the distal end of the manipulandum was sampled every 10 ms. Average position values were calculated for each type of trial. Velocity and acceleration traces were derived by successive numerical differentiation of the average position values. The total force (F_{tot}) acting on the distal end of the manipulandum was the sum of two components: the force exerted by the subject (F_s) and the force due to gravity (F_g):

$$F_{tot} = F_s + F_g \quad (1)$$

The time course of F_{tot} was calculated using the mass and acceleration of the center of mass of the articulated manipulandum, and F_g was computed by taking into account the 15° tilt of the working surface. Finally, F_s was obtained by subtracting F_g from F_{tot} . The term "force" used below refers to F_s .

RESULTS

Some of the results of the experiments with the monkeys were described before (Georgopoulos et al. 1981). The results of the experiments with the human subjects are based on previously unpublished data (A.P. Georgopoulos, J.F. Kalaska, and J.T. Massey, unpublished observations).

General Results

The results described below come from trials in which all subjects performed the task for the first time. All subjects performed the task in a similar way, from the beginning. During a target shift trial, the hand moved initially toward the first target for a period of time depending on the time for which that target stayed on; then, the subject changed direction and moved at a high speed toward the second target, which he captured successfully (see Fig. 2 in Georgopoulos et al. 1981). No errors were committed by the monkeys. The human subjects made errors in 5% of the trials: one-half of these errors was made during control, nontarget shift trials, and were target hold errors. This suggests that the subjects moved as fast as possible because in these trials the subjects went through the target window without stopping; in fact, the peak velocity of the movement in these target hold error trials was about 30% higher than that attained in the trials in which the subjects stopped within the target window. The results below are based on successful trials alone and refer to kinematic and dynamic variables along the 6 to 12 o'clock (Y) axis, on which movements were made. Motion along the X-axis either did not exist or was very small compared with the motion on the Y-axis.

Kinematic and Force Profiles

Figure 1 shows the average position trajectory of movements made by a monkey during target shift trials (ISI = 150 ms, first target at 12 o'clock). Zero time is the onset of the first target. The force profile corresponding to Fig. 1 is shown in Fig. 2. The kinematic and force profiles were initially identical to the control ones, from which they later deviated. A control force profile is illustrated in Fig. 2 by an interrupted line. We analyze in detail below the force profiles because they are sensitive descriptors of the dynamic commands underlying performance in the task.

First Part of the Force Profile

We distinguish two functional parts in the force vs time profile in a target shift trial. The first is from the onset of force application in the direction of the first target (instant b in Fig. 2) until the deviation of the force pattern from the control one (instant c). At trial onset (interval a-b), a steady

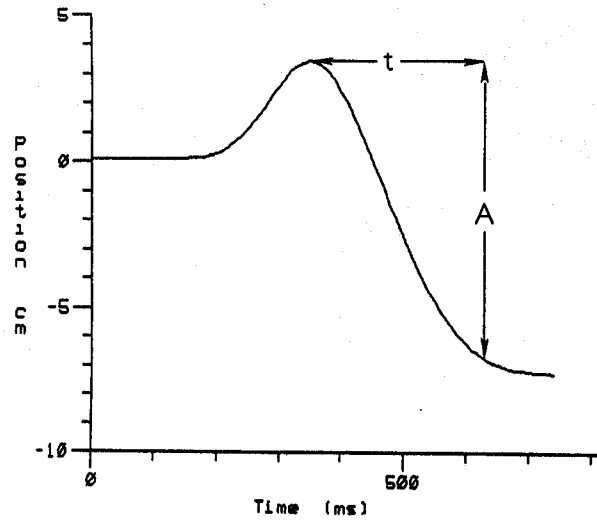


Fig. 1. Position profile fitted on averaged ($n = 15$ trials) data points. Target shift occurred at $ISI = 150$ ms. First target location was at 12 o'clock, second at 6 o'clock. Data from one subject. Amplitude (A) of the second movement is from reversal of position to entrance to target window. Movement time (t) is the corresponding time interval

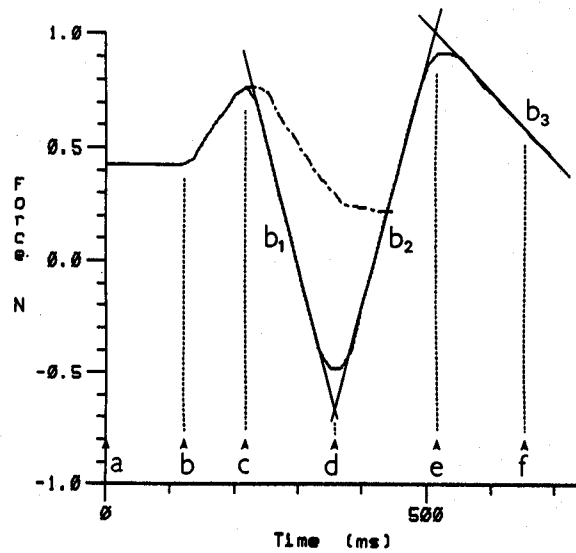


Fig. 2. Force profile fitted on averaged ($n = 15$ trials) data points, corresponding to those of Fig. 1. (See text for explanation of symbols.)

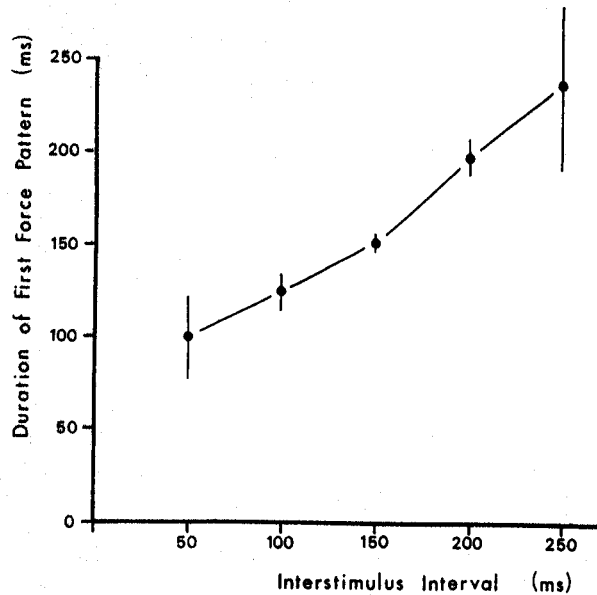


Fig. 3. Duration of the initial force pattern as a function of ISI. Data are mean \pm SD from three human subjects

force was exerted by the subject in order to keep the manipulandum steady at the center LED position. At time *b* a new force was applied in the direction of the first target (at 12 o'clock). The rate of force application in this interval was approximately constant and almost identical to that of the control case. This was true for all the subjects. These results indicate that the subject's strategy was to start the movement as if no change of target would occur. This is understandable for the probability that the target would change was 0.5, so that the subject could not predict whether a particular trial was a control or a target shift trial. The initial, control-like force pattern was applied for a time (interval *b-c*) that increased monotonically with the ISI, that is, the time for which the first target stayed on. This is shown in Fig. 3.

Second Part of the Force Profile

This part corresponds to the time interval *c-f* of Fig. 2, beginning at the deviation from the control pattern (*c*) and continuing until the manipulandum arrives and stops within the target area (*f*). This profile comprises, in turn three parts, each approximating a straight line. The first slope b_1 (Fig. 2) corresponds to the time interval *c-d* (T_1), extending from the onset of deviation (*c*) to the slope reversal (*d*). The second slope b_2 occurs in the time interval (*d-e*) (T_2), from the slope reversal (*d*) to its next reversal (*e*). Finally, the third slope b_3 occurs in the time interval *e-f*, during which the force returns to the static level associated with holding the manipulandum at the target position. This last slope was difficult to determine because of marked variability in the individual values. In contrast, slopes b_1 and b_2 were easy to measure and shared several common characteristics. First,

they were large and of similar absolute magnitude. Slope b_1 was -9.2 ± 2.03 Newtons/s (mean \pm SD, $n = 3$ human subjects), and b_2 was 10.5 ± 2.1 Newtons/s. The difference $|b_1| - |b_2|$ was not statistically significant (paired t -test). Second, the slopes b_1 and b_2 had almost the same value among target shift trials with different ISIs, i.e., they did not vary with the time for which the first target stayed on. Finally, they were applied for approximately the same amount of time. Thus, b_1 was applied for a time $T_1 = 151 \pm 32$ ms (mean \pm SD, $n = 3$ human subjects \times 6 types of target shift trials = 18) and b_2 for a time $T_2 = 136 \pm 52$ ms. The two distributions were not statistically different (Mann-Whitney test). However, the variance of T_2 between trials with different ISIs was three to six times greater than that of T_1 , even in the same subject ($p < 0.05$, F test). It is interesting to note that b_1 was different from, and larger than the equivalent (decelerating) slope in control trials. These results suggest that the subjects adopted a new and stereotyped strategy in this part of the task; they applied large forces to brake the first movement, if needed, and to implement the second movement as fast as possible. Since the slopes b_1 and b_2 , and the corresponding intervals $c-d$ and $d-e$ did not vary appreciably in trials with different ISIs, it can be argued that the distance covered during the interval $c-e$ was approximately the same. In fact, variation of the slope b_3 and its interval $e-f$ were responsible for the increased distance traveled in trials with increasing ISI.

Information Processing of the Second Movement

The large forces applied to implement the second movement resulted in an appreciable increase of the speed of that movement, in spite of the fact that accuracy requirements remained the same. This was achieved by all subjects, monkey and human alike. We calculated the rate of information transmission under these conditions according to Fitts' equation (1954) as follows:

$$I_p = -1/t \log_2(W/2A) \quad (2)$$

where I_p is the information transmitted in bits/s, t is the duration of the second movement time in seconds, W is the diameter of the target window, and A is the amplitude of the second movement. The term $-\log_2(W/2A)$ is the index of difficulty. We measured t and A from the reversal of position until the entrance to the target area (see Fig. 1); W was 2.5 cm. Representative results obtained from one monkey for different target shift trials and control trials corresponding to the direction of the second movement are shown in Fig. 4. It can be seen that the rate of information transmission was greatly increased during the target shift trial, as compared with the control values (C). Moreover, the time course of this increase in the rate of information processing was such that a peak was observed at $ISI = 150$ ms. In contrast, the index of performance was the same in the control case and when the target shifted after an ISI of 400 ms. In the latter case, the first movement was completed and the second was made all the way from the first to the second target location after the hand had already rested at the first target location for a short time. Thus performance returned to control levels. Similar findings were obtained from the remaining subjects. These results indicate that when a movement is generated while another one is being processed, information is processed more efficiently. This has obvious implications as an explanatory principle of the performances in skills involving sequences of movements.

A correlate of this increased efficiency in information processing might lie in the observation by Soechting and Lacquaniti (1983) that under similar conditions of rapid response to a target change

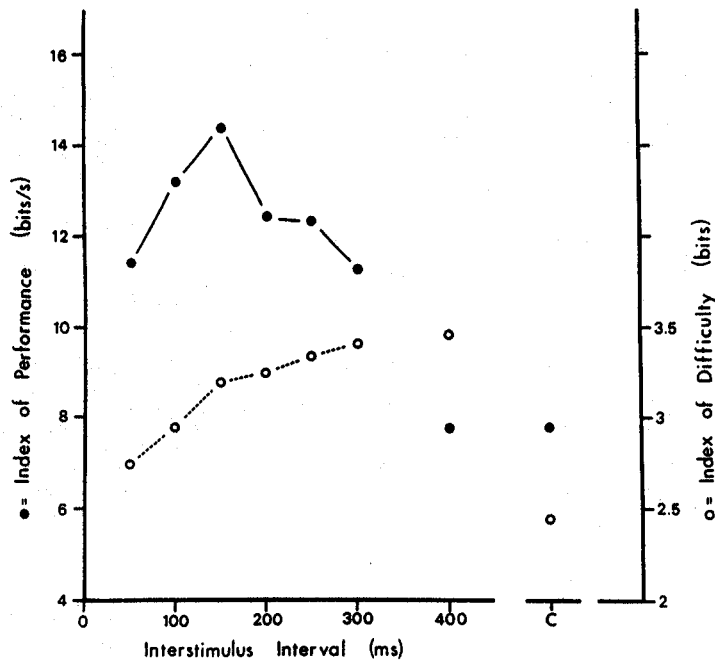


Fig. 4. Index of performance (filled circles) and index of difficulty (open circles) as a function of ISI. Data from one subject. First target at 6 o'clock

there is a reduction in the degrees of freedom of the movement; this is achieved by imposing constraints on the kinematic variables (angular deceleration at the shoulder and elbow joints), and by generating more stereotyped patterns of activity in the muscles acting on these two joints.

Psychological Refractory Period

The time at which the force profile started to deviate from the control profile can be taken as the beginning of the second movement, in response to the shift of target location. Therefore, the time from the onset of the target shift to the beginning of the force deviation can serve as an indication of the time it took the system to process the signal of the second stimulus and to start generating the second movement. This time can then be compared with the corresponding time in control trials, i.e., from the onset of the stimulus until the instant when the force begins to build up. The results are shown in Fig. 5. It can be seen that the times in the target shift trials resemble those of control trials. There was an increase of 46 ms in the case of $ISI = 50$ ms. Although this increase was statistically significant (t-test), it was much smaller in magnitude than that predicted by the equation (Davis 1956):

$$PRP = RT_1 - ISI \quad (3)$$

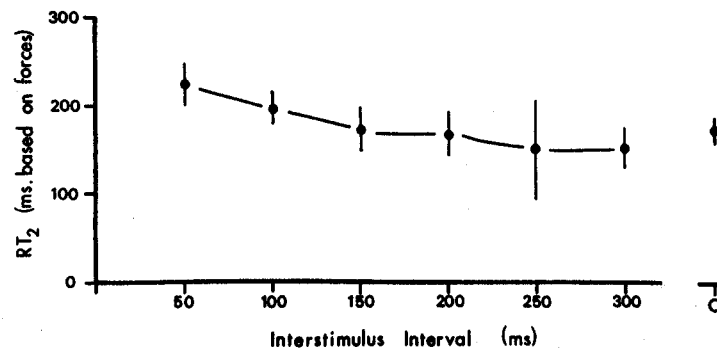


Fig. 5. "Second reaction times" (see text) based on the deviation of the force pattern from the control one, as a function of ISI. Data are mean \pm SD from three human subjects

Based on our force measurements, this predicted psychological refractory period (PRP) was 124 ms. These results are very similar to those described previously regarding the reaction time (Georgopoulos et al. 1981), and to others regarding the torque and electromyogram (EMG) onset times at the shoulder and elbow joints during responses to change of target location in a pointing task (Soechting and Lacquaniti 1983).

A Note on Superposition

The kinematic outcomes of the present experiments were within the framework of a recent hypothesis concerning the formation of the trajectories of hand movements (Morasso 1981). According to that hypothesis, movements are programmed as dome-shaped velocity profiles. A single such profile is considered as representative of a single motor program; by extension, velocity profiles with more than one peak can be regarded as the output of linearly superposed individual profiles (see also Morasso and Mussa Ivaldi 1982). We analyzed the results of the present experiments in light of this idea as follows. We assumed that the velocity profile we observed during target-shift trials is the outcome of two superposed profiles. The first would correspond to the control profile, i.e., the one the subject would make toward the first target in the absence of a target shift. Superposed upon that is a second velocity profile that corresponds to the movement all the way from the location of the first to that of the second target. These profiles are dictated by the respective target location. The second velocity profile was derived from the data; it was the second profile from trials with ISI = 400 ms, in which the first movement was completed up to the location of the first target, and the second movement was made all the way from the location of the first to that of the second target. The second profile was superposed upon the first after a time interval equal to the time from the onset of target to the change of force in the corresponding control trials. The two profiles were added algebraically. An obvious prediction of the superposition is that the peak of the second velocity profile cannot be more than that of the second constituent velocity profile, since the first and second profiles that are added are of opposite signs (corresponding to movements in opposite directions). This prediction was not observed in the actual data. Indeed, peak second velocities in the target shift trials often exceeded those of the movements made all the way from the

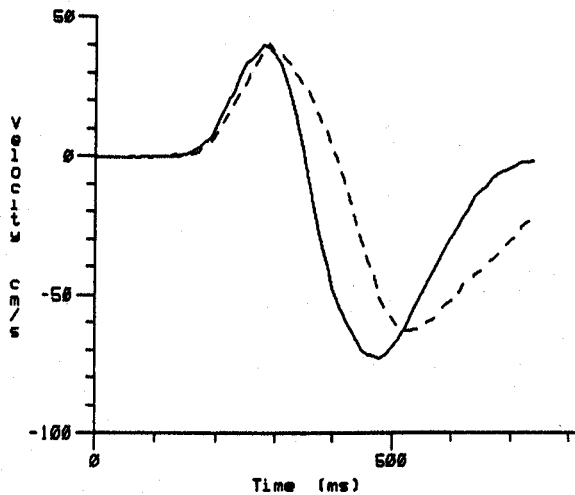


Fig. 6. Observed (solid line) and predicted by the superposition hypothesis (dashed line) velocity profiles. Data from one subject (ISI = 150 ms). (See text for explanation.)

first to the second target. This is illustrated in Fig. 6. In addition, the slopes of the experimentally observed second velocity profile often differed appreciably from, and were steeper than those predicted by the hypothesis. Therefore, we conclude that the results of the present experiments cannot be explained by the superposition hypothesis.

DISCUSSION AND CONCLUSIONS

The subjects were asked to move to a target that changed location during the reaction or movement time. They moved initially toward the first target location, but the movement was truncated and was followed by another toward the second location. This second movement was completed successfully within the accuracy constraints of the task. This task presents a challenge to the motor system, for the generation of the appropriate sequence of forces to successfully perform the task might require, for example, foreknowledge of the dynamics of the initial movement, the relation between force and displacement under the varying dynamic conditions, and of the accuracy constraints. It is remarkable that all the subjects, monkeys and humans alike, employed a strategy from the first trial that dealt with these complexities simply, uniformly, efficiently and effectively. The strategy was *simple*: "move to the target that is on until it shifts; then, move to the new location as soon as possible". How was such a two-part strategy implemented? Since the time of target shift was uncertain, the dynamic characteristics of the movement that was interrupted (e.g., velocity and acceleration at the time of target shift) were also uncertain. Again, a simple solution was found: "apply a large force in the new direction, as soon as possible after the target shift; stop the initial movement and start the new one". This force sequence that was emitted after the target shift appears to be a "default" sequence, consisting of two steep slopes of force change that are opposite in direction, have the same absolute magnitude, and are applied sequentially for about the same interval of time. Moreover, this sequence was *uniformly* applied without distinction in all

cases, in seemingly the same form during trials with different times of target shift. Was this strategy efficient? Maybe not, if physical work is considered, for these large forces would probably be excessive in cases of short target shift times. Yet, it was quite *efficient in terms of information processing*, for it unburdened the system from calculating or predicting the upcoming dynamic parameters and displacements, and, positively, resulted in an appreciable increase of information transmission, as judged by Fitts' index of performance. Finally, the strategy was behaviorally *effective*. Performance was practically errorless from the very beginning, and yet faster. The strategy seems to have been chosen on behavioral rather than mechanical grounds. It apparently took into account the probabilities in the experimental design: control and target shift trials occurred on a 50%:50% basis, hence the initial movement toward the first target. After the target shift, the goal was straightforward: "correct the error (i.e., stop the initial movement, for there is no reward in going to the first target location), and go to the new target as soon as possible (to get the reward)". Under these conditions, one could suppose that the switching of motor commands would be impeded due to limitations of the nature of the PRP. On the contrary, the switching of the commands was not only possible but quick and successful, resulting in accurate performance. It is noteworthy that the switching of patterns of cell discharge was also unimpeded in the motor cortex of monkeys behaving under the same conditions (Georgopoulos et al. 1983). What allowed this remarkable performance? We argued before (Georgopoulos et al. 1981) that the high stimulus-response compatibility in the spatial domain and the fact that only one anatomical unit (the same hand) was the performer lie in the root of these results. It is expected that tasks and devices which take into account these principles would result in improved performance even in more complicated sequential movement tasks.

REFERENCES

- Davis R (1956) The limits of the psychological refractory period. *Q J Exp Psychol* 8: 24-38
- Fitts P (1954) The information capacity of the human motor system in controlling the amplitude of the movement. *J Exp Psychol* 47: 381-391
- Georgopoulos AP, Kalaska JF, Massey JT (1981) Spatial trajectories and reaction times of aimed movements: effects of practice, uncertainty, and change in target location. *J Neurophysiol* 46: 725-743
- Georgopoulos AP, Kalaska JF, Caminiti R, Massey JT (1983) Interruption of motor cortical discharge subserving aimed arm movements. *Exp Brain Res* 49: 327-340
- Morasso P (1981) Spatial control of arm movements. *Exp Brain Res* 42: 223-227
- Morasso P, Mussa Ivaldi FA (1982) Trajectory formation and handwriting: A computational model. *Biol Cybern* 45: 131-142
- Soechting JF, Lacquaniti F (1983) Modification of trajectory of a pointing movement in response to a change in target location. *J Neurophysiol* 49: 548-564