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Research Note

Spatial Control of Arm Movements*

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Summary. Human subjects were instructed to point one hand to different visual targets which were randomly sequenced, using a paradigm which allowed two degrees of freedom (shoulder, elbow). The time course of the hand trajectory and the joint angular curves were observed. The latter exhibited patterns which change markedly for different movements, whereas the former preserve similar characteristics (in particular, a single peaked tangential velocity curve). The hypothesis is then formulated that the central command for these movements is formulated in terms of trajectories of the hand in space.

Key words: Arm trajectories – Multiple degrees of freedom movements – Tangential velocity – Central motor commands

Movements of the arm can be described either in terms of spatial trajectories of the hand or of angular curves of the joints. It is thus important to determine whether the motor commands are centrally represented in terms of joints angles or of spatial trajectories. In order to answer this question, it is possible to observe different movements which correspond to the same motor task and to look for common features among the different movements. This note reports the result of experiments[1] in which human subjects were instructed to point one hand to different visual targets which were randomly sequenced.

The experimental paradigm was chosen in such a way as to simplify the problem as much as possible: only two degrees of freedom were allowed (wrist movements were prevented by means of a splint) and the influence of gravity was kept constant by working in the horizontal plane. In this way, movements of the arm were reduced to flexion-extension of the elbow and flexion-extension of the shoulder (Fig. 1). Motions of the arm were transduced by means of a light-weight two-joints articulated structure[2] whose handle was grasped by the subjects. Trunk movements were prevented by appropriate strapping.

Six adults[3] participated as subjects in the experiments, during which the six targets were activated according to a sequence[4] which was repeated five times, with a small rest time between trials. The subjects received no particular instruction except simply to reach the target position. No contact occurred between hand and target because the target was on the plate and the arm was underneath. The potentiometers on the shafts of the two joints pro-

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1 The experiments were performed in the laboratory of Prof. E. Bizzi (M.I.T., Psychology Department, Cambridge, MA, USA). Stimulus activation and data acquisition were managed by means of a PDP 11/10 computer with a LPS 11 peripheral unit. Subsequent data analysis and stimulation was performed on a PDP 11/34 computer, at the Electrical Engineering Department, Genoa University, Italy

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2 The articulated structure was designed by Prof. N. Hogan (M.I.T., Mechanical Engineering Department, Cambridge, MA, USA) and was built using aluminum pipes. The proximal pipe was 28 cm long, the distal pipe was 36 cm long and the axis of the distal pipe was displaced by 3 cm from the hinge of the proximal pipe. These dimensions and the relative position between the manipulandum and the body were chosen in such a way to avoid any constraint on the freedom of motion of the handle

3 Data on the subjects:

Subject	1	2	3	4	5	6
Sex	M	M	M	F	F	M
Age	25	24	36	23	31	31
Humerus length	33.5	32.5	31	26	32	27
Forearm length	41	34	38	34	33	37

4 The activation sequence of the targets included 30 targets, it was randomized in space and in time, with an average activation interval of 3 s

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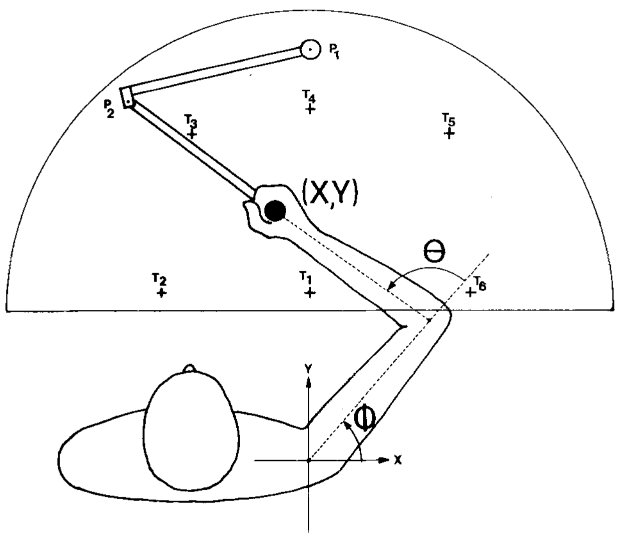


Fig. 1. Experimental setup for the study of reaching movements in the horizontal plane. Recorded variables: (X, Y) Cartesian Coordinates of the Hand, (Φ, θ) Angular Coordinates of the Joints (wrist movements were not allowed). Visual targets: $T_1, \ldots T_6$. Their cartesian coordinates, with regard to the shoulder origin, are the following ones (in cm); T_1 (0,0), T_2 (–30,0), T_3 (–25,30), T_4 (0,35), T_5 (30,29), T_6 (30,0). Only one target was active at one time. When one target was switched off, another one was switched on and the subject was instructed to move the hand from the former to the latter. The target plate was about 1 inch above the plane of the arm and the subjects had no vision of their hand

vided the source signals which were digitized at 10 ms/sample, and allowed the computation (by means of simple trigonometric calculations) of the following variables: (1) the trajectory of the hand in the X–Y plane, and (2) the angles at the shoulder and elbow joints[5]. The digitized angular signals were then fitted by means of a least-squares, second-order polynominal approximation which allowed the estimation of the first and second time derivatives. The same technique was used with the X–Y trajectories in order to estimate the tangential velocity of the hand.

The results of the experiments are presented in Figs. 2 and 3. Figure 2 shows the spatial trajectories of the hand and Fig. 3 shows the time course of the joint angular position, joint angular velocity, and hand tangential velocity, for four different movements. Joint angular velocities (Fig. 3, second row) for these different movements exhibit quite different patterns; some joint angular velocities are single peaked and some are double peaked (which means inversion of the joint motion). The four movements of the figure exhibit all the four possible combinations (single peak/double peak) for the two joints.

In contrast, the tangential hand velocity for the different movements has a single peaked curve that varies little in shape between movements. The duration of the different movements was rather constant for each subject, whatever the shape of the joint angular patterns. This is in accordance with previous observations (Bryan 1892; Stetson and McDill 1923). If we now look at the trajectories of the hand (Fig. 2), we observe that they approximate straight segments which link initial and final positions.

In sum, the observations above may be summarized by saying that the common features among the different reaching movements are the single-peaked shape of the hand tangential velocity and the shape of the hand trajectory. As a consequence, one may hypothesize that the central commands which underlie the observed movements are more likely to specify the trajectory of the hand than the motion of the joints (in short, we may call it a "spatial control" hypothesis). The idea of "spatial control" can be associated with early theoretical and recent experimental investigations. Noting the "deeply seated inherent indifference of the motor control centre to the scale and position of the movement effected", Bernstein (1935) formulated the hypothesis that there exist in the higher levels of the CNS projections of space and not projections of joints and muscles".

Considering the problem of serial order in behaviour, Lashley (1951) hypothesized the existence of systems of space coordinates: "their influences pervade the motor system so that every gross movement of limbs of body is made with reference to the space system. The perceptions from the distance receptors, vision, hearing and touch are also constantly modified and referred to the same space of coordinates". More recently, Russell (1976), studying the accuracy of pointing one hand to a target, starting from different initial positions, concluded that "spatial location is a viable alternative to the stored motor commands or their sensory consequences in the production and control of movement". Furthermore, the experiments of Viviani and Terzuolo (1980) provide a detailed kinematic description of the hand motion during handwriting which shows that the basic kinematic variables (tangential velocity of the hand and curvature of the trajectory) preserve their temporal pattern when position and size of the movement is changed.

It is also interesting to note that the same kind of problem is being faced in the robotic field. Even if most industrial robots presently used are controlled according to joint-oriented schemes, the need of

5 Unwanted small translations of the shoulder determine errors in the estimated joint angles. These errors are non linear functions of the angles and of the length of the arm segments. To give an order of magnitude, it is possible to calculate that, for an arm configuration in which the shoulder angle is $\pi/4$ and the elbow angle is $\pi/2$, a shoulder displacement of 1 cm determines an error of one and two degrees in the two angles, respectively

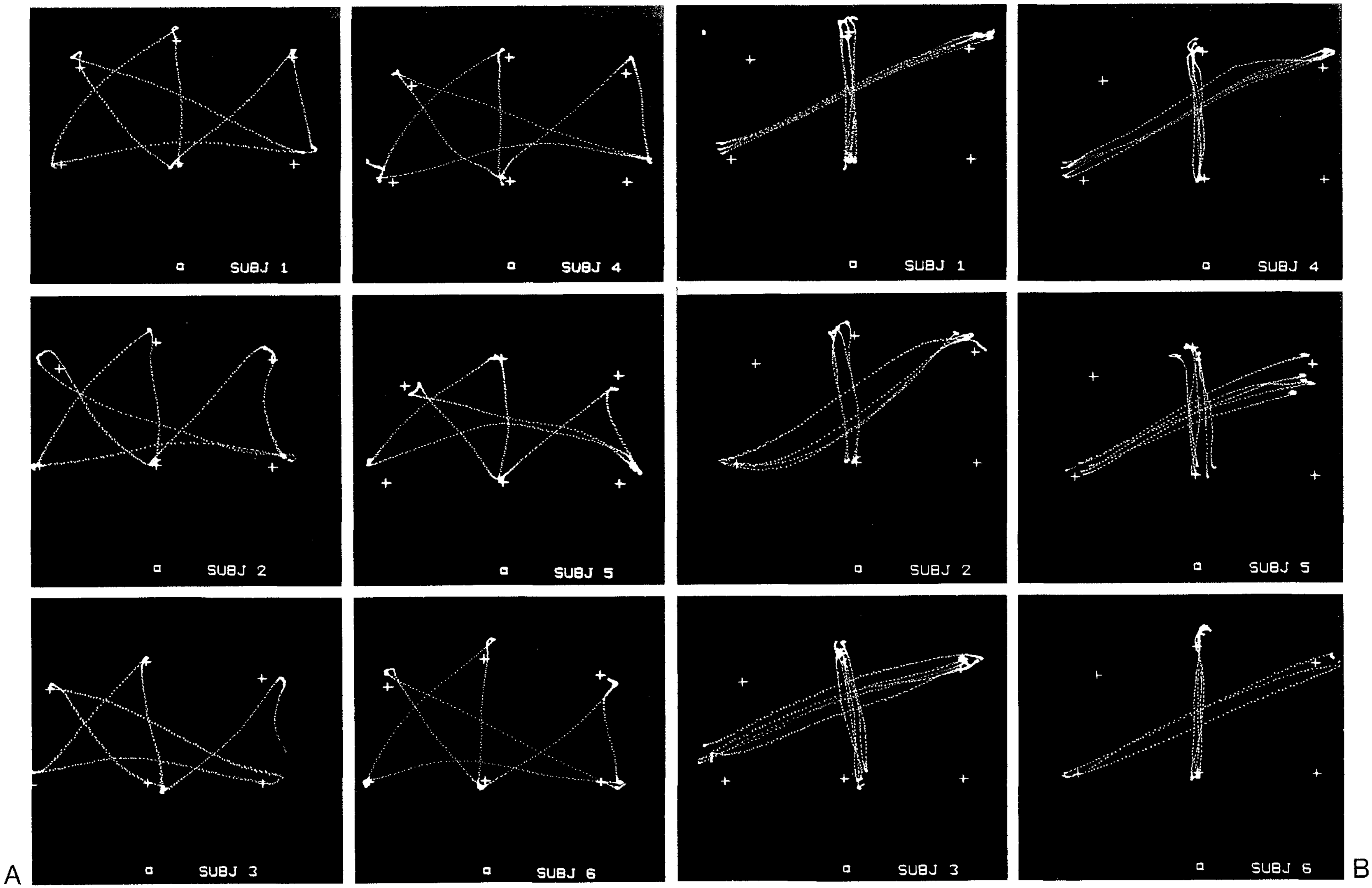
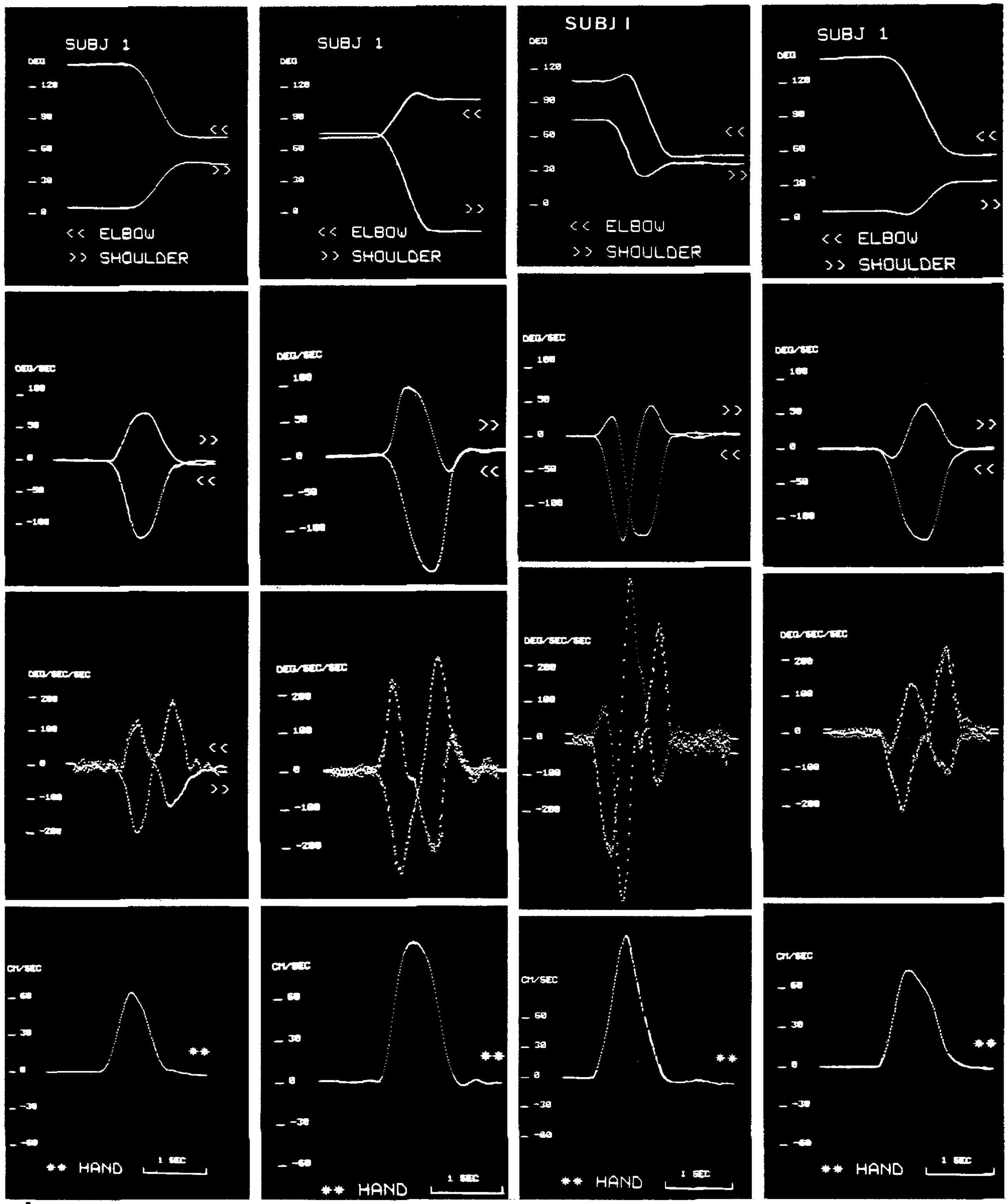


Fig. 2A, B. Spatial trajectories of the hand. The crosses indicate the target positions and the square indicates the shoulder position. The trajectory was sampled at 100 samples/s. The distance between the first and the second target (see Fig. 1 for target numbering) is 30 cm. **A** The sequence of movements is generated by the following sequence of targets: 1, 4, 2, 6, 5, 1, 3, 6. **B** Several repetitions of two movements are superimposed



A B C D

Fig. 3A–D. Joint rotation and hand trajectory. For subject 1, this figure displays the temporal patterns of four typical movements (a column for each movement) which exhibit distinctive joint angular patterns, though preserving the shape of the tangential velocity curve. For each movement, the following curves are displayed: Row 1: Joint angle (vertical scale: 30 deg); row 2: Joint angular velocity (vertical scale: 50 deg/s); row 3: Joint angular acceleration (vertical scale: 100 deg/s/s); row 4: Tangential hand velocity (vertical scale: 30 cm/s) (time scale: 1 s). **A** Target 1 to target 4. **B** Target 3 to target 5. **C** Target 2 to target 5. **D** Target 1 to target 5 (see Fig. 1 for target numbering) task-oriented control systems is favoring the emergence of concepts of "spatial control" (see, for example, Nevins and Whitney 1973; Paul 1979). On the other hand, it is important to realize that the notion of "spatial control" implies the existence of a mechanism for transforming spatial motor commands into coordinated joint angular patterns (see, for example, the models of Pellionisz and Llinás (1980) and of Benati et al. 1980a, b).

Finally, it is possible to speculate that the rationale of this seemingly complicated control architecture lies in the potential of the "spatial code" to serve as a common language among the different sources of information which subserve coordinated movements (e.g., exteroceptive and proprioceptive afferences, motor programs, etc.).

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