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The Coordination of Eye, Head, and Arm Movements During Reaching at a Single Visual Target*

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Summary. The time of occurrence of eye, head, and arm movements directed at the same visual target was measured in five human subjects. The latency of activation of the corresponding neck and arm muscles was also measured. It appears that although the overt movements are sequentially ordered (starting with the eye movement, then the head and finally the arm) the EMG discharges are synchronous with respect to the eye movement onset. In addition, eye movement latency appears definitely (though weakly) correlated with either neck or arm EMG latencies. Neck and arm EMG latencies are also mutually correlated. These results indicate a clustering of segmental motor programs for target oriented actions.

Key words: Eye-head-hand coordination – Eye movement latency – Biceps and neck EMG latencies – Central motor commands

The action of reaching a visual goal by hand involves a sequence of segmental movements. In normal conditions a subject will first orient his gaze, then his head, and finally his arm in the proper direction. We attempted here to provide a more complete description of the pattern of coordination of these segmental movements and of the related muscle commands. Available data from the literature answer our question only partially. Studies of eye-head coordination show that, although in the overt sequence the eye movement usually precedes that of the head (Whittington et al. 1981) activation of the neck muscles occurs some 20–40 ms prior to the beginning of the eye movement (Bizzi et al. 1971, Warabi 1977). In other studies, dealing with eye-hand coordination, the overt hand movement has been shown to lag the eye movement by 60–100 ms, according to several authors (Angel et al. 1970; Prablanc et al. 1979). This delay is to be compared with the classical delay of about 100 ms between the contraction of agonist arm muscles and the resulting limb displacement.

From these data one gains the impression that the command forwarded to the different muscular groups involved in reaching would be clustered within a very short span of time, although the sequence itself would be the expression of the peripheral force field associated to the eye, head and arm movements. Definite conclusions however, can only be drawn from a recording of the complete set of events in the same subjects and during the same sessions. Under such conditions, a study of the precise temporal organization of the muscular commands for reaching might reveal some of the constraints which have to be taken into account at the central level for the programming of motor sequences.

Material and Methods

Five adult subjects participated in the experiments. During sessions the subject was seated at the center of a semicircular table (96 cm radius) on which targets were presented. Targets were red (600 nm) light emitting diodes positioned on a circle at 60 cm from the body. One target was at the center of the display (central target) and the others were placed at 10°, 20°, 30°, and 40° on each side. The table was covered with an isotropic resistive paper fed with a current in the concentric dimension. Position of the right hand was recorded by monitoring the contact with the table of a thimble attached to the subject's forefinger (Prablanc and Jeannerod 1973). A logic pulse was generated when the finger lost contact with the table, i.e., at the onset of an arm movement. No recording was available during the movement itself. Horizontal head movements were recorded continuously by way of a helmet (400 g) secured to the subject's head. The helmet was connected to a low-torque potentiometer by a cardan device. Binocular horizon-

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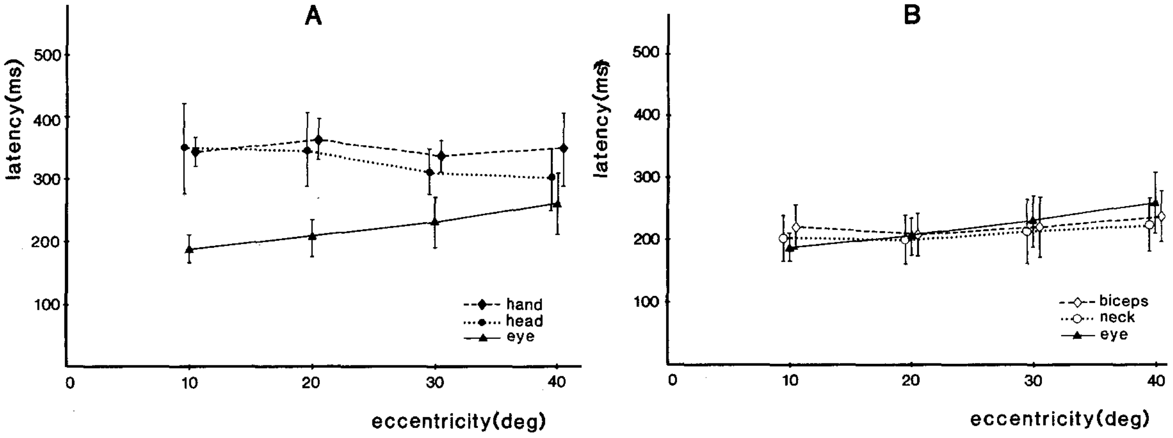

Fig. 1A, B. Mean latency of overt segmental movements and of the corresponding EMG activation. **A** mean latency (in ms) and SD for hand, eye, and arm movements as a function of target distance (eccentricity, in degrees of arc). **B** mean latency and SD for eye movement and biceps and neck EMG. Data for this figure are averaged from the five subjects. They have been obtained in the closed-loop session, i.e., the session with visual control of the hand movement available

tal eye movements were recorded by the EOG technique using Beckman electrodes. The amplifier was equipped with a counter-drift system. Bandpass was between 0 and 30 Hz with a 6 db/octave attenuation. The electromyographic (EMG) activity of the biceps brachialis of the right arm and of the right posterior neck muscles (splenius capitis, splenius cervicis and semispinalis capitis) was recorded bipolarly (Venables and Martin 1967) using Beckman surface electrodes. EMG was displayed either directly (0–300 Hz bandpass) or as a rectified signal by using a continuous mean voltage technique. All responses were recorded on a paper chart and on magnetic tape.

Subjects were instructed to track the targets when they appeared, by eye, head and hand as quickly and as accurately as possible. No instruction was given as to the sequence of the movements. At the beginning of a trial the central target was on. The subject had to keep his finger pointed to it and to fixate it by eye until another target appeared. The hand was tranported with the arm fully extended. The subject first had to raise his arm (a movement controlled, at least partly, by the biceps) and then to rotate his shoulder joint. Targets were presented in a random order and at random intervals. Targets remained on for 3 s. The subject had to come back to the central target between trials. Each target was presented ten times. Only those responses directed at targets appearing on the right side of the central target were considered for analysis.

Each subject underwent two sessions. In one session the visual surrounding was illuminated. Subjects could see their hand prior to, and during their movement. During the second session the room light was turned off. Only the targets were visible, no visual information from the moving limb was available.

Time was measured between the onset of each target and the following events: ocular saccade, head movement, hand movement (as signalled by the digital pulse), biceps EMG and neck EMG. For EMG, the relevant measure was a rise of the rectified signal corresponding to about 15% of the maximum amplitude reached by this signal on each trial.

Results

In the five subjects the ocular saccade was always found to be the leading event in the reaching sequence (Fig. 1A). Its latency tended to increase slightly but significantly ($p < 0.001$; F-test) with distance of the target from the midline, in agreement with previous findings (Bartz 1962; White et al. 1962; Prablanc and Jeannerod 1974). The onset of the head movement lagged behind that of the eye movement, although it had a reverse relation to target distance: the latency of head movements was longer for targets close to the midline (351.7 ms for 10 deg) than for more remote targets (305.7 ms for 40 deg). Since the latency of the corresponding neck EMG was approximately constant over the range of target distance (see below), this effect could have been due to a longer duration of the isometric contraction of the neck muscles (i.e., the time between onset of EMG and onset of movement), for low amplitude head movements. A more technical (and more likely) explanation, however, would be that the rise time of head movements would be slower for low amplitude movements. Mean velocity of head movements was between 25°/s for 10 deg and 65°/s for 40 deg. Consequently, the difficulty in detecting the movement would delay artificially its true onset. This problem did not exist for arm movements, which had a constant latency of about 350 ms over the full range of target distance. In this case the arm movement onset was detected as the time at which the hand raised from the table, a vertical component of the movement which can logically be assumed to be uninfluenced by target distance.

A completely different pattern of the act of reaching was observed when the onset of EMG activation, rather than the onset of the movement, was used as an index for the measure of latency (Fig. 1B). The latency of either biceps or neck EMG

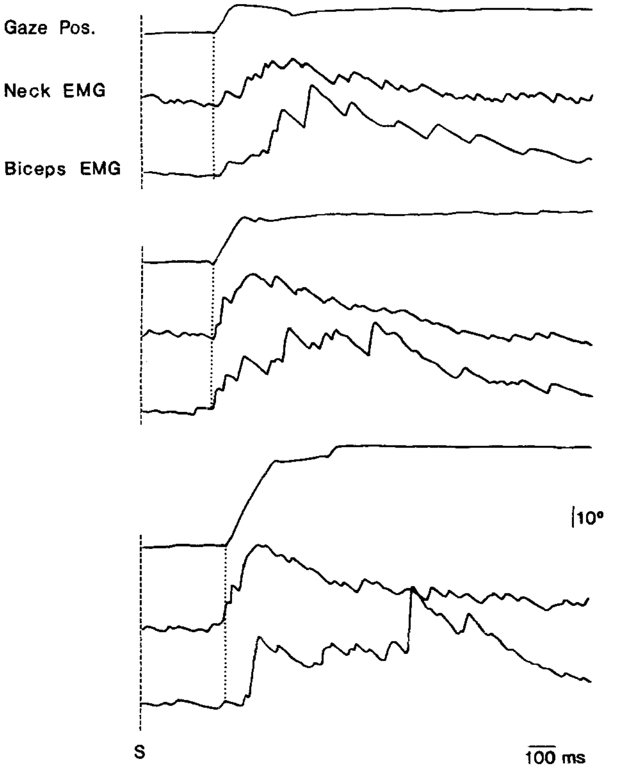

Fig. 2. Eye-movement-EMG synchrony in reaching movements. Data have been sampled from one subject reaching for a target at 10 deg from the midline (upper row), 20 deg, and 40 deg (lower two rows). Gaze pos. indicates gaze position, which is the algebric summation of eye position and of head position. EMG traces are integrated envelopes of rectified EMG discharges. S indicates the onset of the target. Onset of the eye movement is indicated on the records by a vertical dotted line

was found to remain within values of 200–220 ms and to be uninfluenced by target distance from the midline. In addition, the maximum difference between the mean values of latency of the two muscle groups did not exceed 17 ms, a difference which was never found to be significant. When compared to the latency of the eye movement, biceps and neck EMG latencies appeared to be slightly shorter. A significant 20–30 ms difference ($p < 0.05$) was found for targets located at 40 deg. For targets located at 20 or 30 deg, the difference was even smaller and did not reach significance. Finally, for targets located at 10 deg, the pattern reversed and the eye movement latency became systematically shorter than that of biceps and/or neck EMG. Since the EMG of extra-ocular muscles could not be recorded in this experiment a constant value of about 7 ms should be substracted from eye movement latency. This duration has been estimated on the monkey to correspond to the duration of the isometric contraction of the extra-ocular muscles (Fuchs and Luschei 1970; Robinson 1970). It can be assumed that a similar value also holds for man.

Table 1

	Conditions	r	Slope
$T_N = f(T_E)$	CL	0.34	0.47
	OL	0.38	0.50
$T_B = f(T_E)$	CL	0.41	0.47
	OL	0.39	0.47
$T_B = f(T_N)$	CL	0.51	0.48
	OL	0.42	0.38

Correlation coefficients (r, Bravais-Pearson test) and slopes of linear fitting for pairs of latencies

T_N: latency of neck EMG activation; T_E: latency of ocular saccade; T_B: latency of biceps EMG activation

CL: closed-loop condition: visual reafferences from the movement are available

OL: open-loop condition: no visual reafferences available

The degree of relative synchrony of the onset of biceps and neck EMG activation, and of the onset of eye movements (Fig. 2) was further investigated with a correlation analysis (Bravais-Pearson test). The values of individual pairs of latencies (eye movement-biceps EMG; eye movement-neck EMG; biceps EMG-neck EMG) were plotted against each other for each session. The effect of the target distance was suppressed by an intra-subject normalization of the data. Under these conditions a definite correlation was found for each of the three pairs of latencies. Although they were significant at the 0.001 level, correlation coefficients were below $r = 0.5$. Similarly, the slopes of the linear fitting were in the range of 0.45 (Table 1).

The overall pattern of the sequence of eye-head-arm movements, as well as the timing of EMG activation were found to be uninfluenced by changing the condition of visual control of the movement. No significant difference could be observed either in the latency values, or in the degree of correlation between the session where visual control of the movement was available and the other session, where it was not.

These results stress the fact that the neural commands forwarded to different moving segments (e.g., eye, head, arm) implicated in the same act of reaching are generated in parallel. The lack of effect of changing the visual conditions of movement execution on the timing of EMG events can also be regarded as an attribute of a centrally generated motor pattern. Such a clustering of motor commands has an obvious advantage (with respect to a serial type of organization) in achieving a faster mobilization of the motor ensemble related to the goal. The question of how such a synchrony could be obtained is a matter of speculation. One possibility could be that the commands would in fact be released by a signal from a common generator. The main characteristics required from this signal would be to carry information as to the location of the target on a body-centered map of visual space. Such a characteristic could be met by a feedforward signal issued from the eye-movement generator, since eye-movements are likely to be coded in spatial, rather than in retinal, coordinates (Mays and Sparks 1980). This hypothesis, however, is not completely confirmed by our experimental data: at least for targets distant from the midline EMG latencies for arm and neck muscles can be clearly shorter than the eye movement latency, even if the 7 ms isometric contraction time of extraocular muscles is substracted. In addition, a "spatial" generator located outside the eye-movement generator would better account for the relatively loose correlation that we found between eye-movement latency and arm and neck EMG latency.

The relative synchrony of neural commands for eye, head and arm movements, in producing a correlative sequence of the overt movements, may also have an important implication for eye-hand coordination. It has been shown in experiments using a similar situation (Prablanc et al. 1979) that subjects make relatively large pointing errors when they are not allowed to move their head and their eye toward the target. This would suggest that foveal fixation of the target (which may be completed before the arm movement has even started) can provide cues for a precise guidance of the arm at the target.

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