Invariant temporal characteristics of manipulative hand movements

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Summary. The measurement of eight manipulative serial hand movements showed a clear distribution of their temporal characteristics into two distinct groups. When the hand was used as a sense organ during active touch the finger movements across objects were restricted to a slow performance range below 2 Hz. Recordings from single mechanoreceptive afferents and calculations of their receptor densities indicated that these movements have to be slow to match the temporal requirements of the sequential sampling process from the mechanoreceptor populations. In contrast, manual skills not associated with the collection of sensory information like handwriting, typing or pencil shading, were performed rapidly. Their frequencies were close to those of fastest possible tapping. Evidence is provided that the different frequency groups are associated with distinct sensory control processes. The low frequency group represents movements involving focal sensory control (Julesz 1984). The high frequency group is not performed open-loop but monitored by preattentive sensory processes. The results indicate a dual sensory control mode operating in separate frequency domains of movement.

Key words: Hand movements - Cutaneous mechanoreceptors - Active touch - Motor control - Sensory control of movement - Humans

Introduction

The functional organization of the oculomotor system into saccadic and pursuit eye movements with clear differences between their sensorimotor and temporal properties has no counterpart in the skeletomotor system. The characteristic speed of the two types of eye movement reflects the operation of two independent control systems that transform the visual and vestibular inputs into the respective motor behaviours. These properties rendered the two categories of eye movement particularly suitable for thorough system analysis.

Limb muscles can also produce ballistic, open-loop and continuous, closed-loop movements resembling the saccadic or pursuit type, but these can be transformed voluntarily and gradually into each other, representing a continuum of possible performances rather than distinct categories. That does not preclude that natural limb movements also fall into categories with different characteristic speed and sensory control modes. This question could not hitherto be pursued, because a systematic study of natural motor acts was not possible until recently, due to the lack of appropriate techniques.

The human hand seems particularly suitable for the study of sensorimotor behaviour because of its large motor repertoire and fine somatosensory and visual control. We have performed an analysis of hand movements using an optoelectronic two-camera system utilizing light-emitting diodes. A set of eight natural hand movements was selected for the study. Four were tasks employing the hand as a sense organ in which the subject had to identify a tactile object, and four were automized manual skills (tapping, writing, pencil shading, typing). Surprisingly, the temporal features of the two task groups were distinctly different. Evidence is provided that these different temporal properties are due to the involvement of different sensory control modes. The slow digital scanning movements during active touch are performed to collect high-acuity somatosensory information from the finger pads, whereas the fast performance of the four non-tactile hand skills only require coarse 'preattentive' sensory feedback controlling the
largely predicted trajectories. On the basis of these results we propose that the association of characteristic narrow tuning characteristics of motor acts in the time domain with different sensory control processes may represent a more general principle in sensorimotor control.

Methods

Subjects
Experiments were performed on 20 naive healthy volunteers aged 19 to 34 years. 19 subjects were righthanded, one lefthanded. In all experiments the dominant side was investigated. Handedness was not tested but solely taken as the hand preferred by the subject.

Recording technique
Motion analysis of various types of sensorimotor tasks including slow exploratory as well as rapid hand movements was performed by an optoelectronic two-camera position analysis system (Selspot II). Selspot II utilizes infrared light-emitting (wavelength 920 nm) diodes (LEDs) mounted on a small plastic plate (7 x 13 x 2 mm) and powered by a LED control unit. LEDs were fixed to the fingers. The system was calibrated by means of a position reference structure of known dimensions with four attached LEDs. For calibration as well as for motion analysis position data of LEDs were amplified, AD-converted (12-bit precision) and delivered to a camera interface module (CIM) which converted serial data to parallel data. Control and buffer (FIFO FBPM NS150) modules were utilized for communication with an external PDP 1173 computer.

LEDs were monitored at 100 Hz during data acquisition periods of 6-10 s. A VT 125 terminal provided both real time display of LED positions and also produced graphical displays of position and movement velocity. Hardcopies of these data were made on a LA 75 companion printer.

Selspot data were collected using the Selspot software system supplemented by our own programs for spectral analysis of the movements. Frequency analysis of the main sine wave component of different movements was performed, since the everyday performances tested consisted of surprisingly regular repetitive cyclical movements. With spectral analysis the frequency of the main component could be assessed and other major components could also be detected if present. In addition, the regularity of each particular manual activity could be assessed from the amplitude and shape of the spectral peaks and their relation to the remainder of the spectrum.

Experimental procedure
The subject was seated in a comfortable chair with the hand under study centered in the calibrated three-dimensional space. The forearm rested on a table and the hand was free to move. For tactile scanning finger movements the forearm was semipronated and the wrist fixed to the table by a cuff. LEDs were attached with adhesive tape on defined sites of the hand or arm as described below. The subject was instructed to perform the tasks either at the naturally preferred speed or, for tapping, at maximum possible speed, depending on the particular task.

The following sensorimotor tasks were investigated:
1. Tactile discrimination of object shapes and surface textures. Blindfolded subjects were asked to scan consecutively a small wooden ball (diameter 1.2 cm), a cube (length of side 1.0 cm) and the surface texture of a metal disk covered either with plastic or grained sandpaper (diameter 2 cm). LEDs were fixed to the radial side of the index finger and the ulnar side of the thumb (see Fig. 1A). The distance of the LEDs from the volar side of the thumb and forefinger was approximately 0.3 cm. The subject was instructed to continue exploring throughout the recording period of 6-10 s, also after recognizing the object or surface texture, in order to detect additional features such as small elevations that might have been mounted on to some objects.

2. Pencil shading and handwriting
With one LED attached to the distal part of a ball-point pen the subject was asked to pencil shade on a paper sheet placed on a table in front of him. Handwriting was investigated in the same way. The subject was instructed to pencil shade and to write his name at his naturally preferred speed. Pencil shading and writing movements were also imitated with one LED attached to the moving forefinger, and the subject was asked to perform these movements with the finger instead of the pen.

3. Repetitive tapping movements
The purpose of these studies was to find out the maximal frequencies of various alternating movements. The subject was asked to tap the thumb against the index finger as fast as possible. LEDs remained attached as for tactile scanning. In 11 subjects alternating movements performed as rapidly as possible at the hand, forearm and shoulder were also studied in the following way: Hand movements: flexion-extension movements were performed at the wrist. Forearm movements: flexion-extension movements at the elbow joint were studied. One LED was fixed on the dorsal side of the distal forearm. Shoulders movements: with the arm extended and one LED attached to the lower arm repetitive abduction-adduction movements at the shoulder joint were analysed.

4. Typewriting
LEDs were fixed to fingers 2-5 of each hand of six skilled typists in order to analyse the temporal movement characteristics during typing. This task is different from the other performances because the keys are pressed by different fingers of both hands, thus representing sequential finger movements rather than repetitive movements of the hands or cooperative finger activity during exploratory finger movements.

Microneurographic recordings
In some experiments microneurographic recordings from single low-threshold mechanoreceptive afferent fibres innervating finger pad skin were performed by means of tungsten microelectrodes inserted into the median nerve in the upper arm. Afferent activity was recorded while subjects identified by touch surface textures and object shapes. The investigation of the response of cutaneous mechanoreceptors during active touch was not complemented by that of passive tactile stimulation, because it is difficult to imitate precisely the cyclical pattern of movement and the change of pressure applied to the receptive skin field as it occurs during active touch. Informed consent was obtained from all subjects and recordings were approved by the ethics committee of the hospital. Details of the recording system and the experimental procedure have been described elsewhere (Kunesch et al. 1987). Afferent units were classified according to both their discharge properties and their receptive skin fields as slowly adapting type I (SA I), slowly adapting type II (SA II), fast adapting type I (FA I) and fast adapting type II (FA II), as previously described (Johansson and Vallbo 1979).

In one of the subjects the widths of the epidermal ridges of