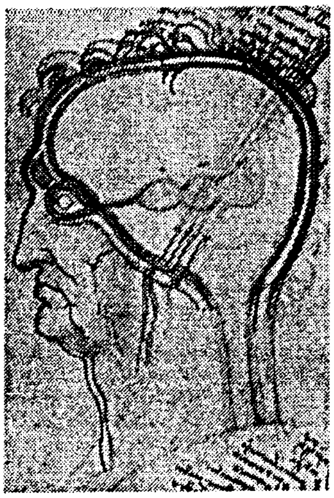
Current research in motor control II

Theories, implementations and research perspectives in motor control



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Zbigniew Waśkiewicz, Grzegorz Juras, Joachim Raczek

University School of Physical Education in Katowice
2004

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The present book is the outcome of the International Conference on Motor Control organized at Wisła, Poland, 22-24 October 2004.

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ISBN 83-87478-72-5

Typesetting: BiuroTEXT Bartłomiej Szade

Printing: UKiP J&D Gębka, 44-100 Gliwice, ul. Pszczyńska 44, tel. 231-87-09

Publishing House of University of Physical Education in Katowice 2004
Edition 200 copies

Skill Acquisition and Motor Memory in the Control of Pointing Movements

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For an easy task like moving the luminous spot of a laser-pointer across a projection screen from one location to another, representations of visual targets in extrapersonal space must be transformed into a kinesthetic reference frame (Lacquaniti, Caminiti 1998; Tillery, Flanders, Soechting 1991; Soechting, Flanders 1989). Errors in this sensorimotor transformation can result in a goal not being reached immediately or a dithering of the laser-spot around the target which may be traced back to visual information (Adamovich, Berkinblit, Fookson, Poizner 1998).

However, accepting the notion that the CNS controls the acceleration of an actor's extremities plus any additional masses of a carried tool (e.g. laser-pointer) in a time coordinated way in order to reach a precise destination on a projection screen, it is essential that the CNS has a well established memory of the movement dynamics. This memory is known as an internal model of the task and consists of implicit and explicit knowledge of the physical properties of the body and environment (Konczak, Jansen-Osmann, Kalveram 2003; Shadmehr, Holcomb 1997; Shadmehr, Thoroughman 2000). If one assumes that the desired output signal is the input which the CNS uses to control motion, then the controller must essentially be an inverse of the controlled system (Kalveram 1992; Karniel 2002; Shidara, Kawano, Gomi, Kawato 1993). The deviation of the actual from a desired sensory outcome provides error values which might be functionally used to stabilize the

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plant's impedance along the trajectory (Burdet, Osu, Franklin, Milner, Kawato 2001; Kalveram, Schinauer, Beirle, Richter, Jansen-Osmann 2004; Harris, Wolpert 1998; Wolpert, Ghahramani, Jordan 1995).

Most rapid goal directed movements can be considered to be highly overlearned, and therefore to produce individually stereotyped velocity profiles in their trajectory course (Wolpert, Ghahramani 2000). The learning assumption, however, does not actually solve the motor control problem which arises from the necessary translation from spatial to force units whilst realizing a desired movement. Visual and kinesthetic information must be merged with reference to an internal model of force control. We assume that the merging of sensory information is based partially on the mechanisms of oculo-motor control for tuning the adjustable pattern generator (Cruse, Dean, Heuer, Schmidt 1990; Houk, Buckingham, Barto 1996; Neggers, Bekkering 2001). Empirical support comes from animal studies which show that fixation neurons in the superior colliculus encode the distance between current and desired gaze positions (Bergeron, Guitton 2000). Furthermore, it has recently been found that the internal online-monitoring of a reaching trajectory follows parietal-cerebellar circuits, a finding which supports both the predictive capability of an inverse model and the essentiality of kinesthetic state feedback (Desmurget, Grea, Grete, Prablanc, Alexander, Grafton 2001). Hypothetically, when a sensorimotor transformation does not need an inverse model of the task, isotonic and isometric muscle contractions should not only be comparable intrinsically (Ivanova, Garland, Miller 1997) but also with regard to predictions of the sensory consequences in exteroceptive coordinates.

Thus, leaving us with the question: Is it possible to learn and retain the sensorimotor transformation without kinesthetic state feedback of the limb – a problem which may be highly relevant for rehabilitation purposes?

Method

Subjects

5 female and 5 male adults participated in the study. One female was left-handed. Subjects' age ranged between 21 and 51 years (m = 36.2 sd = 8.3). All participants gave written informed consent to take part in the study for

which ethical approval was granted by the appropriate committee of the Heinrich-Heine-University.

Apparatus

Participants sat within a head-centred semi-circle projection screen (radius 1.5 m) and viewed two bright arrows projected onto the screen. A "target-arrow" specified the goal, and a "feedback-arrow" indicated the actual angular position of the forearm in eye-centred coordinates in a reference experiment (real movement). In an isometric experiment the "feedback-arrow" on the screen was controlled by the amount of pressure placed by the fixed arm against a strain gauge. Force was integrated on-line in order to produce a comparable speed of the "feedback-arrow" to the reference experiment. Subjects' right forearm was inserted into an orthosis that was driven by a torque motor allowing horizontal one-jointed flexion and extension movements from the start position of 90°-inclination relative to the upper arm. A damping coefficient of 0.5 Nm/rad/s was constantly administered to make the subcutaneously perceivable pressure comparable within both experiments. The arm was automatically returned to the start position after each movement. The room was dimmed and the arm was blocked from view.

Procedure

Prior to each movement trial the participants saw the goal, located at 28.65 degrees to the left or right of the mid-saggital. After 1.5 s an imperative tone signaled movement onset. A block consisted of 40 trials, each of which lasted 8 seconds. The movement experiment started with an open-loop pretest pointing block in which both arrows were cut from view when the arm began to move (crit: 2 deg/s). Open-loop pointing was meant to obtain a baseline of visual-kinesthetic correspondence. A first learning block with visual feedback was used to establish visual-kinesthetic correspondence. A second learning block should lead to an individually consolidated torque profile with regard to this correspondence. Using open loop pointing again in a forth block, we measured the degree to which visual-kinesthetic correspondence was retained. After a short break of about 10 min the subjects began the isometric force control experiment in which the same ABBA-design was administered. Both experiments were run under two different visual feedback learning conditions, i.e. "knowledge of results feedback" (KR) in which both the "target-arrow" and the "hand-arrow" reappeared after movement end, versus "trajectory feedback" (AK) in which the "hand-arrow" was visible over the entire trajectory course. The different visual feedback conditions occurred on different days.

Data Analysis

Angular position and torque data were filtered offline to remove noise. With regards to the consolidation of individual trajectories during the prolonged learning, data of the second learning block were aggregated over trials. The individual torque profiles were considered as being an optimal, i.e. desired, profile. This profile was then subtracted from the data of each open loop pointing trial by computing the difference along the entire trajectory course in values of root mean square error (RMSE [N]). Thus, the individually transferred internal model to conditions of open loop pointing following the four distinct learning situations was compared with a MANOVA procedure (2x2x5 within subjects design): The factor "TASK" contained the level "MOV", i.e. the real goal directed forearm movement and the level "ISO", i.e. the "isometric pointing". The factor "VISFB" contained the levels KR and AK, and in the 5-level factor "SEQUENCE", the entire 40 trials were consecutively aggregated in order to form 8 trials per sequence.

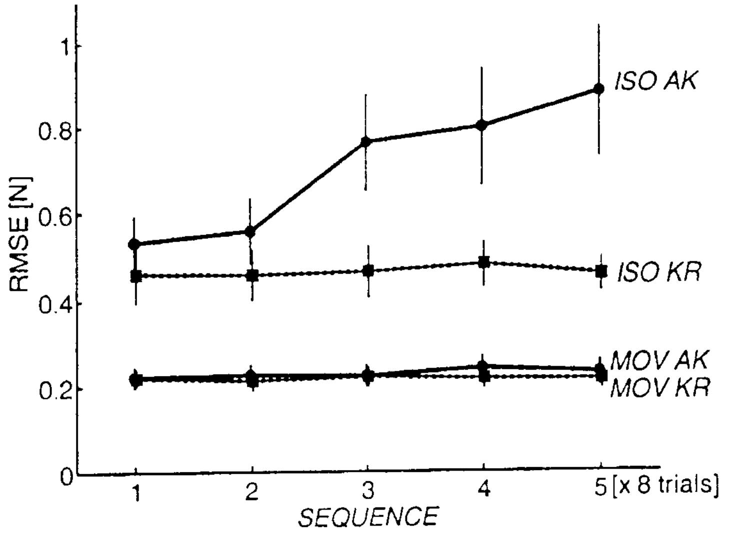

Fig. 1. Open loop deviation from the individually optimal torque profile acquired during learning under different tasks and visual feedback conditions.

Results

Little was learned within the skill acquisition phase of real goal directed flexions and extensions because real movements with full kinesthetic state feedback naturally have a good pre-existent visual-kinesthetic correspondence.

Thus, a very strong task effect on retention shows the lack of a comparable performance under conditions of experimentally constrained kinesthetic state feedback ($F(1,9)=58.67$, $p<0.001$) and real movement. The consolidated individual torque profiles from the second learning block were nearly retained over the entire course of open-loop pointing with real movement, independent of the applied visual feedback. A comparable result in the isometric force control task was only realized when the skill acquisition phase contained "knowledge of results", i.e. when "target-" and "feedback-arrows" were visible after movement end. This is expressed by a significant second order interaction ($F(4,36)=4.90$, $p<0.01$). Thus, the dramatic forgetting of an internal control model can only be ascribed to force control learning in which the entire movement trajectory was visible ($F(4,36)=4.50$, $p<0.01$).

Discussion

The task effect clearly shows that kinesthetic state feedback of a real movement is necessary to retain an internal model of force control in an optimal way. The visually performed external control of a plant (here "hand arrow") suffers dramatic deteriorations of performance. With respect to its task difficulty of constrained kinesthetic feedback, the sensorimotor transformation can only be nearly learned. However, knowledge of results seems to be an adequate training procedure in order to retain a highly reproductive memory of force control, at least for the given time course of 40 trials. Although an on-line vision (i.e. trajectory feedback) generally provides advantages regarding accuracy, even for very rapid movements (Elliot, Helson, Chua 2001), an internal model of force control can be retained better when the movement itself is not visible. The improved retention may be attributed to a better focusing of attention onto the external target whilst learning (Wulf, Shea, Park 2001). Trajectory feedback may entail current control of movement (Elliot, Helson, Chua 2001) which may also impede memory consolidation (Shadmehr, Holcomb 1997) because attention must be distributed along the entire trajectory course.

This idea is currently supported by the finding that a special kind of neuron in the monkey superior colliculus, the visuomotor neuron, known to be centrally involved in saccade preparation, is also important for covert shifts of attention (Ignashchenkova, Dicke, Haarmeier, Thier 2004).

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