

Adaptation motor learning of arm movements in patients with cerebellar disease

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Abstract

Objective—To design a test of motor learning using arm movements in normal subjects and patients with cerebellar disease.

Methods—Elbow angle was continuously displayed as a cursor (a dot) on a computer screen, and subjects made ballistic elbow flexion and extension movements to try to move the cursor between two targets on the screen. The relation between the arm movement and its visual feedback was changed, and the subjects reacted by adapting the amplitude of their movements in subsequent trials.

Results—The consecutive errors showed exponential learning curves during adaptation, which were quantified by their steepness. Ten patients with isolated cerebellar or olivopontocerebellar degeneration had less steep learning curves than normal subjects, indicating a failure of adaptation motor learning in cerebellar disease. The results show that this test may be useful for the analysis of motor learning.

(*J Neurol Neurosurg Psychiatry* 1996;60:515-519)

Keywords: motor learning; ballistic arm movements; cerebellum

Motor learning of various types can be tested depending on the conditions of the motor task or the feedback information provided.¹ Paradigms used to test learning in humans are adaptations of motor control to visual feedback altered with distorting prisms,²⁻⁴ learning of tracking movements with normal or mirror reversed vision,⁵ and simple conditioning of the acoustic blink reflex with electrical stimuli.^{6,7} Distorting prisms have proved especially useful for testing motor adaptation,^{3,8} reviving the findings of Helmholtz in 1867.⁹ In this test, the altered visual feedback induces a systematic mismatch between the normal coordinates for the hand position and the actual, visually perceived, position. The adaptation to this mismatch is a learning process. In other words, the recalibration of the movement with respect to an artificially altered visual feedback is tested.

Our knowledge about the physiology and anatomy of motor learning is still incomplete. Various cortical and subcortical areas must be intact for motor learning to take place. One of the most extensively studied anatomical struc-

tures is the cerebellum. Marr¹⁰ and Albus¹¹ suggested that simple adaptive motor behaviour is regulated through two types of input to the Purkinje cells: (1) advance information from central structures via the pontine nuclei, and (2) additional "teaching" signals from peripheral feedback via the climbing fibre input mediated through the inferior olive. This hypothesis was reinforced by direct recording from Purkinje cells during a learning task.^{8,12} Thus it is not unexpected that motor learning would be affected in patients with cerebellar disorders, as already shown with other paradigms.^{2,3,5,7} In the present experiment, we studied patients with cerebellar or olivopontocerebellar atrophy with a computer based paradigm that quantitatively describes the adaptation process. Similar tests have been used to analyse the metrics of learning movements in humans¹³ and monkeys.¹⁴

Methods

We studied 10 men with cerebellar disease, aged 20 to 64 (mean 47.5) years. Seven patients had pure cerebellar atrophy (three hereditary cases and four sporadic cases) and three patients had olivopontocerebellar atrophy (two hereditary cases and one sporadic case). The diagnosis was based on clinical examination, pedigree information, and MRI of the brain. None of the patients with pure cerebellar atrophy had definite extracerebellar signs, but of the patients with olivopontocerebellar atrophy two showed rigidity and one orthostatic hypotension and resting tremor. Clinical signs of the cerebellar disease were rated on a scale of cerebellar function.¹⁵ In addition to the overall score, a subscore was obtained by rating only upper limb ataxia, upper limb hypertonia, and postural tremor to specifically measure the cerebellar deficit in the patients' upper limbs. Control subjects were 10 normal volunteers, aged 25 to 67 (mean 52.2) years. The protocol was approved by the clinical research subpanel, and all subjects gave their written informed consent for the study.

MOTOR LEARNING PARADIGM

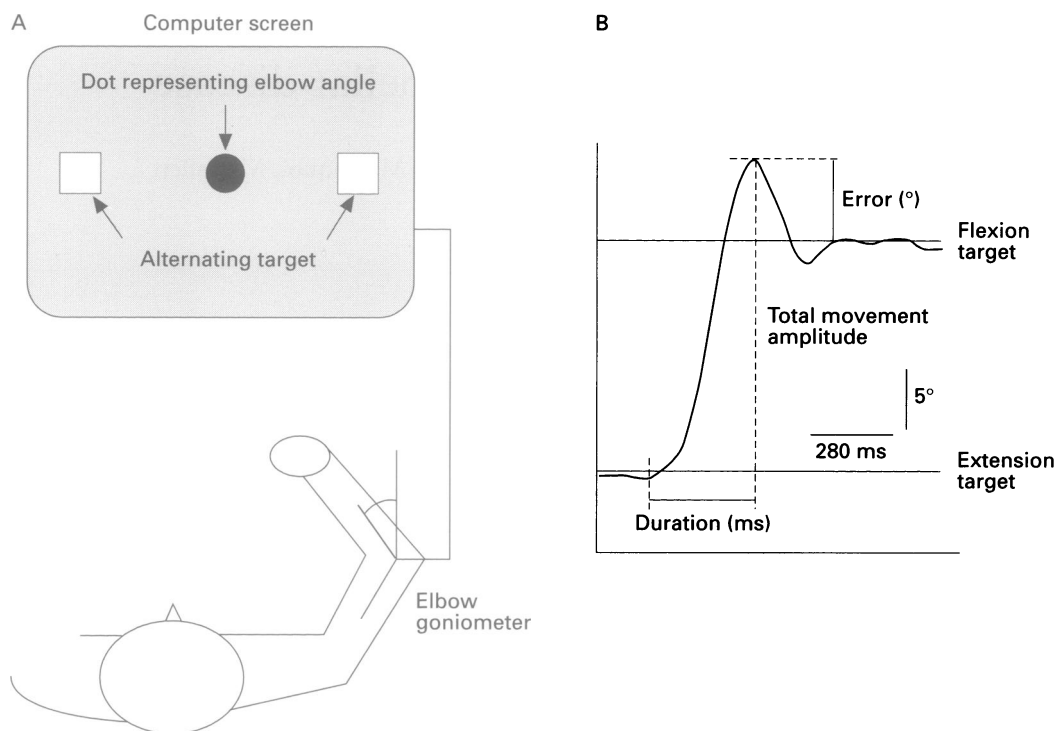
The motor learning task was to match a ballistic movement of the forearm to a target alternating between two positions on a computer screen (fig 1A). The subject sat facing the screen at a distance of 1 m. The forearm (right or left) was fixed to a lever with adhesive tape at the wrist and proximal forearm. The lever was fixed to a platform so that the elbow joint

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Received 10 March 1995
and in revised form
12 September 1995
Accepted 12 September 1995

Figure 1 (A) Schematic drawing of the experimental paradigm. The subject sits 1 m away from the screen of a personal computer, and the forearm is fixed to a lever that measures the elbow angle. Displayed on the screen are a cursor (dot), representing the elbow angle, and a target (squares), which alternates from one side of the screen to the other every five seconds. (The cursor and target are enlarged for clarity.) (B) A typical ballistic movement, and the scales for calculating movement duration, movement error, and total movement amplitude of a single trial.



could be freely moved over an angle of more than 40° with a convenient neutral position of about 70° elbow angle. The angular displacement was continuously monitored with a goniometer fixed to the axis of the lever. The resolution of the goniometer was approximately 0.01° . The elbow angle was digitised (100 Hz) with an A/D board and displayed and stored on line in the computer. A target (0.4×0.4 cm square) alternated every five seconds between two positions on the screen separated by a distance of 13.5 cm. Elbow joint angle was represented on line on the screen by a cursor (0.2 cm dot), which was controlled by the lever movement. The positions of the target and lever were continuously stored in digital format for later off line analysis.

The subject had to make the cursor follow the alternating movements of the target with a single, rapid elbow flexion or extension, with emphasis on speed rather than accuracy. He was told that it was critical to maintain the velocity of the arm movement and was reminded that this was not a reaction-time task but that every movement could be consciously prepared.

The gain between arm and cursor movements was adjusted so that an elbow rotation of 13.5° resulted in a 13.5 cm cursor displacement (gain = 1.0 cm/ $^\circ$). After a few practice trials, the subject performed 40 movements between the right and the left targets (baseline trials). Between trials 40 and 41, the gain of the system was suddenly increased so that an elbow rotation of 9.5° produced a cursor displacement of 13.5 cm (gain = 1.42 cm/ $^\circ$), and the subject performed another 40 movements between the targets (test trials).

DATA ANALYSIS

The movement error and the total movement amplitude (measured in degrees of elbow

angle) and the total movement duration (ms) were analysed for each single trial from both the right and left arms (fig 1B). The duration of the ballistic part of the arm movement was defined as the time between the first deflection and the first turning point of the lever position signal. Overshoots were considered positive errors and undershoots negative errors. Flexion and extension movements were analysed independently, but as they did not differ much with respect to errors, they were included as consecutive trials in the subsequent analysis. Mean values were calculated across trials for both groups of subjects.

For normal subjects and patients, the mean error values for the baseline trials (x_1 – x_{40}) were subtracted from the mean error values for the test trials (x'_{41} – x'_{80}). The values x'_i were subsequently fitted with an exponential curve according to a least squares algorithm (Number Cruncher statistical system) with the formula:

$$y'_i = 4 \cdot e^{-x'_i/\tau} \quad (i = 41-80)$$

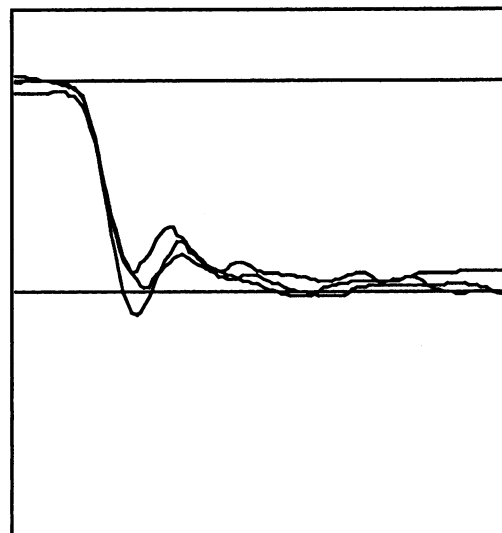
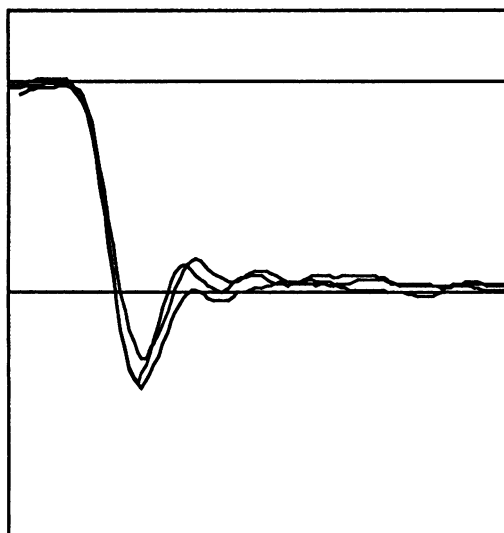
This exponential fit was applied to data from each individual subject and to the group averages. The constant 4 was chosen because change of the gain corresponded to a 4° amplitude difference of the arm movement. Because the test trials were normalised to the baseline error, no constant term was added. With this procedure, τ represents half of the trials necessary for the adaptation to the baseline error. The smaller τ is, the faster the adaptation. The quality of the fit was estimated by the mean of the absolute residuals of the first 15 test trials (trials 41–56).

Results

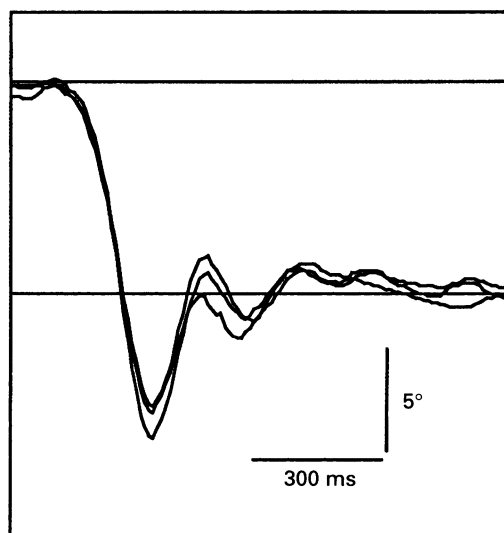
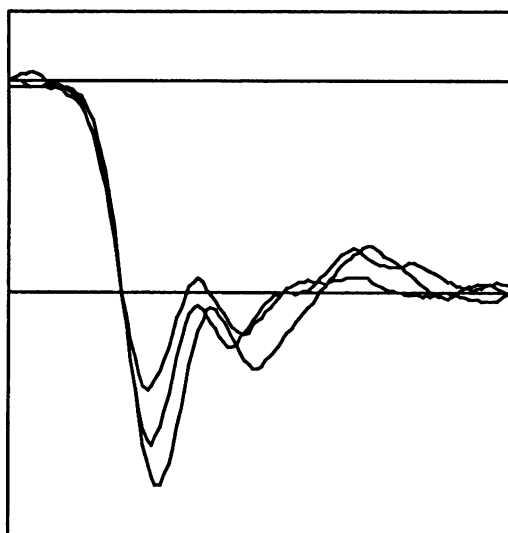
The patients' cerebellar impairments ranged from mild to severe, and all patients had a

Figure 2 Representative examples of movement trajectories in a normal subject (A) and a patient with cerebellar atrophy (B). The first three movements after the change of the gain (trials 41–43) are shown on the left panels and the last three movements (trials 78–80) are shown on the right panels. The patient has a larger error than the normal subject in the beginning movements, but the major difference is that the normal subject shows better adaptation than the patient. The upper horizontal line corresponds to the starting position, and the lower line is the target position.

A Normal subject



B Patient



rather symmetric cerebellar syndrome. Typically, the ballistic arm movements resulted in overshooting the target (fig 1B), but a series of brief corrective movements brought the cursor into the final target position. After the gain was changed, the normal subjects' earliest test trials showed a consistent overshooting of the ballistic movements with a well defined end of the ballistic part of the movement, and the last few test trials showed remarkable precision of the individual movements (fig 2A). The patients' error was larger than the normal subjects' error immediately after the change of the gain, as well as during the later trials (fig 2B).

In the baseline trials, normal subjects showed only minimal improvement of performance over time, as defined by a reduction of target overshoot (fig 3). After the gain was increased, the movement error increased, but rapidly improved in subsequent trials. After six trials, the error had returned to a nearly constant level that was slightly higher than in the

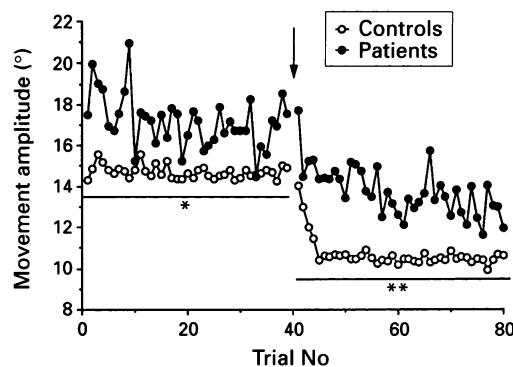
baseline trials. The mean error in baseline trials 11–40 was slightly larger (0.2°) than the error in the test trials (trials 52–80), but the difference was not significant (two tailed paired *t* test).

The patients' movement errors were higher and varied more than those of normal subjects (fig 3). After the gain was increased, only a slow and gradual decrease in error occurred in the subsequent trials.

The duration of the baseline movements was longer in the patients (mean 353 ms) than in the normal subjects (mean 287 ms). Increase of the gain, however, did not affect the mean duration in either group.

Normalising the error values obtained after the change in gain was justified, as there was no difference in the mean error values between trials 20–40 and 55–80 for either the normal subjects or the patients. Figure 4A shows the resulting mean error values and the fitted exponential curve ($\tau = 1.662$) for the normal subjects. The exponential fit indicates that the

Figure 3 Mean movement amplitude ($^{\circ}$) in trials 1–80 for normal subjects and patients. The movement error is the difference between the amplitude of the movement required to reach the target (as indicated by the horizontal lines: *with a gain of 1 $\text{cm}/^{\circ}$ and **with a gain of 1.4 $\text{cm}/^{\circ}$) and the amplitude of the actual movement. The arrow indicates the instant at which the gain was changed.



error was reduced to half of its initial value between trials 42 and 43. Figure 4B shows the normalised mean error values and the fitted exponential curve ($\tau = 9.328$) for all the patients. Although the mean residual value (RV) for trials 41–56 was higher in the patients (RV = 1.122) than in the normal subjects (RV = 0.345), the exponential fits

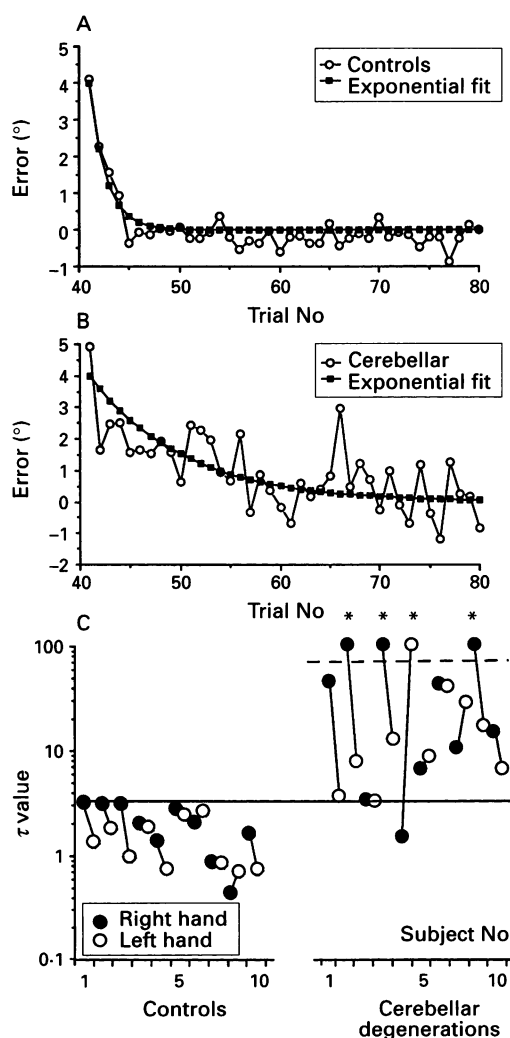


Figure 4 Normalised mean error values and exponential fits for normal subjects (A) and patients (B). The τ values (C) are larger in patients than in normal subjects ($\tau = 9.33$ v $\tau = 1.48$). The horizontal line (in C) indicates the upper limit of the normal values +2SD. Asterisks indicate the four arms for which data could not be included in the analysis, as no adequate curve fits could be obtained due to the large scatter of the error values. Their values were arbitrarily set to equal 100 (above the dashed line).

indicate slower learning in the patients.

In most patients, the τ values for each arm were higher than those in the normal subjects (fig 4C), indicating that the acquisition of learning was slower in patients than in normal subjects. (Data from four arms in the patient group could not be analysed, as no adequate curve fits could be obtained due to the large scatter of the results.) There was a significant correlation between the τ values and the clinical rating subscore for the upper limbs (Spearman rank correlation, $P < 0.01$).

Discussion

Motor learning studies have been performed during acquisition of motor skills and adaptation learning.^{5-7,16-18} The task used in the present study tested the ability of a subject to adapt the movement amplitude of the arm to a changing feedback signal. Relevant to the learning process is proprioceptive information from the moving arm and visual information on the relation of the hand to the defined target. The task exemplifies a common everyday condition. Reaching arm movements depend on such a calibration procedure, which usually involves feedback from visual cues. The natural calibration procedure is done continuously. In our paradigm, we broke up the continuous learning process into discrete events by introducing ballistic movements, the accuracy of which can be measured. It became clear that, even when adapted, normal subjects and cerebellar patients performed the required ballistic movement by overshooting with the first movement and then reaching the final position in one or several oscillations around the target. The physiological effects of these ballistic elbow movements have been studied in detail.^{19,20} When we chose ballistic arm movements, we assumed that we were dealing mostly with "open loop" movements, which are not subject to "on line" correction. A closed loop adaptation paradigm with a similar experimental approach has been used in monkeys with emphasis on the changing of the metrics during adaptation.¹⁴

The error of the initial ballistic overshoot underwent a rapid amplitude reduction after change of the gain, reflecting motor adaptation. The fitted curves of the learning process were used as a comparative measure of the learning efficiency of different subjects. According to this criterion, the motor performance of both normal subjects and patients with cerebellar or olivopontocerebellar degeneration showed clear differences. The error values of the baseline trials were much higher in the patients than in the normal subjects, reflecting the presence of ataxia. Nevertheless, it seems justified from theoretical reasoning, as well as from our data, to assume that, with change of the gain, the mean error value would be similar after the learning process and during baseline conditions. Therefore, to extract the underlying learning process after change of the gain, the relative error (with respect to the baseline error) is more important than the absolute error. Thus our

approach to analysis of the data seems to represent a valid measure of the learning process that occurs in this type of motor learning. The result is similar to the one obtained in a patient with cerebellar cortical infarction and another with olivary hypertrophy by use of a similar learning paradigm.^{13,21}

Our findings can be interpreted in terms of the Marr¹⁰ and Albus¹¹ model of cerebellar learning. In their model, the pontocerebellar mossy fibre system should mediate information on the desired aim of the movement and on visual feedback. The olivocerebellar projection is thought to contribute to the proprioceptive feedback signal.¹⁰ The final output signal of the cerebellum would help to improve the control of the arm position. We found abnormal motor learning in the patients with olivopontocerebellar atrophy, as well as those with pure cerebellar atrophy. This finding may serve as an argument that the cerebellum itself, and not only its afferent pathways, has an important function in motor learning, at least for paradigms of motor learning involving stereotyped simple arm movements.^{15,7} In as much as there is a trade off between the accuracy and the speed of a movement,²² we had to determine whether the duration of the movement would increase or decrease after the gain was changed. It remained constant, so Fitts' law²² cannot account for the different learning efficiency in the patients and normal subjects. The cerebellar cortical area responsible for this kind of learning has been localised in monkeys, by reversible blockade of various areas with muscimol, as a small region in the extreme lateral hemisphere.²³ Dysfunction of this same area may be the basis of adaptation learning failure in patients with cerebellar disease.

We thank Dr F Aiple for help with statistical analysis of the data, Mrs B Guschlbauer for evaluation of the data, Mrs W Vasold for editorial assistance, and Ms B J Hessie for skilful editing. GD was supported by the Deutsche Forschungsgemeinschaft.

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