

## Dynamics of the learning of a morphokinetic movement sequence in humans

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### Abstract

We studied the dynamics of the process through which subjects build a visuomotor representation in memory as they learn a morphokinetic movement sequence presented on videotape. It was hypothesized that recall accuracy is closely tied to the dynamics of the movement-representation process. When analyzed in the form of time series, recall performance should exhibit a deterministic inter-trial relationship reflecting the memorization activity. Twelve subjects divided into two groups recalled a sequence of arm movements 60 times. The model was presented to Group 1 (G1) on all 60 trials, whereas Group 2 only saw the model on the first 30 trials. During these first 30 trials, the analysis of accuracy time series pointed out the short-term historicity of the deterministic inter-trials relationship. For the last 30 trials, this deterministic relationship disappeared in both experimental conditions, except for two subjects of G1, and was replaced by a white-noise process suggesting that a stable representation of the sequence has been built in long-term memory. © 2002 Elsevier Science Ireland Ltd. All rights reserved.

**Keywords:** Visuomotor memory; Dance movement; Time series; Autoregressive Integrated Moving Average

Reproducing a sequence of motor forms relies on morphokinetic motricity in which movements are body-centered and assessed with respect to a reference standard (the model). When the model is no longer visible, recall of this type of sequence requires building a mental representation or an internal reference to guide the action [1]. This visuomotor representation is constructed during the learning process via the repeated presentation of the model, which triggers a reorganization process of information about the memorized pattern [5] and shares the same properties as motor representation built through physical practice [6,10].

However, even at the end of the learning process, recall performance often varies and the recalled sequences are never identical to the model [5].

In a visuospatial map learning experiment, Giraudo and Pailhous [5] used time series methods to study the construction of a memory representation via what they called a ‘migration process’. This process is manifested in the accuracy of the recall. One can assume that the most accurate mental representation (the one closest to the model) is the one stored in memory at the end of the learning phase, when the accuracy curve reaches its maximum. In this view, varia-

tions in recall performance are the expression of the maximum level of accuracy (the accuracy level at which the representation cannot come closer to the model) and the intrinsic variability of the mnesic system, an inherent characteristics of all biological systems. The authors were also interested in variations between two consecutive configurations produced by subjects. This measure of variability between successive recalls accounts for a second process they called ‘structuring process’. The dynamics of this process takes the form of a relaxation curve, with a steady state they called ‘level of memory consistency’. According to the authors, the dynamics of the two processes are independent.

In this study, we analyzed the time course of the learning of a sequence of motor forms presented visually using a time series method. A time series is a collection of observations considered sequentially and ordered in time [3]. The behavior observed at a given moment is supposed to be affected by the behavior at the preceding moment. When a movement sequence has to be learned, mnesic and motor processes must be activated as learning progresses to enable retention and future recall of the sequence. The goal of a time series analysis of recall performance is to identify and model the processes at play in the inter-trial relationship that emerges.

This method also allows one to study recall performance

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variations, and to determine whether they are caused by errors in the mental representation and/or in the motor output. Deviations observed at the end of the learning process have often been interpreted in terms of noise or random errors, but this interpretation has been questioned. The variability observed in this case should be regarded as a partial expression of the variability inherent to any biological system, i.e. as the expression of a positive potential permitting the adaptability and flexibility of human action [7]. A time-series analysis of recall performance can be useful in this respect: based on inter-trial variability, it indicates what part of the phenomenon is purely stochastic and what part is deterministic. So, new interpretations of errors and/or variability can be envisaged.

Accordingly, recall performance at different times in the course of the learning process appears to be determined by the evolving visuomotor representation under construction. Variations at the beginning of the process will therefore be great and largely accounted for by errors in the representation. Later, when motor representation reaches its peak level of accuracy, i.e. the level at which it cannot come any closer to the model, the variations should be mainly due to variability in the mnemonic system. At this point, withdrawal of the model should have no impact on recall accuracy since performance is determined by a stable representation in long-term memory. The time series containing the entire set of trials should thus exhibit a deterministic relationship that reflects the cognitive processes underlying movement-sequence memorization.

Twelve right-handed women aged 18–23 served as subjects.

The task consisted of reproducing a sequence of right arm movements as accurately as possible. The model was presented on a television screen placed in front of the subjects. The sequence had four phases. In the starting position, the right arm was extended across the body with the hand at the height of the left thigh. The first two phases consisted of left-to-right ‘waves’ in the frontal plane ‘drawn’ by the arm, with the elbow initiating the movement. The first phase was executed at chest height, whereas the second was a broader movement in which the arm rose above the head and then came back down along of body side. The third phase was executed in the sagittal plane, with the hand moving away and guiding the arm as it drew two thirds of a circle at the height of the right thigh. The sequence ended with a small wave at hip height, comparable in amplitude to the first one, which brought the arm back to its starting position (arm crossing body, hand at left thigh).

The subjects were randomly divided into two groups (Group 1, G1; Group 2, G2). G1 recalled the sequence 60 times, and the model was presented right before each new trial. G2 performed the first 30 recalls similarly as G1 and the last 30 trials without the model. Testing was individual in both groups. Before the experiment started, the model was shown twice for the purpose of familiarizing the subject with the sequence.

The subject’s motor performance was recorded by a motion analysis system (VICON 370) using two infrared cameras, at a sampling rate of 50 Hz and a precision level of 0.5 cm. The movement of the right hand was recorded by means of a passive marker placed at the end of the middle finger. The analysis focused on the vertical displacement of this marker, assuming that the vertical axis concentrated the most relevant information about the performed pattern. To eliminate non-representative artifacts, the finger-movement data were smoothed using an inverse Fast Fourier Transform, with a cut-off frequency of 5 Hz. In order to allow mutual comparisons, each data sample (including the model sequence) was normalized in time over 300 data points, and normalized in space on a scale ranging from 0 to 100, representing the minimum and maximum amplitudes (Fig. 1). This normalization in time and amplitude preserved the essential spatiotemporal features of our series, and constituted a necessary step for the computation of our dependent variables, based on point-to-point calculations between series.

Recall accuracy was assessed using the root mean square error (RMSE) between a recalled sequence and the model sequence. This measure expressed the mean deviation of a recalled sequence from the model. It was calculated on each trial to obtain a time series composed of 60 values.

Performance variability was measured using the RMSE between two successive recalled sequences. We obtained for each subject variability series of 59 data points.

Accuracy data were analyzed per blocks of five trials; an analysis of variance (ANOVA) 2 (Groups)  $\times$  12 (Blocks) with repeated measures on the second factor revealed no significant difference between groups ( $F(1, 10) = 0.505$ ;  $P = 0.49$  ns), but a significant Blocks effect ( $F(11, 110) = 13.99$ ;  $P < 0.0001$ ). Post-hoc comparisons (Scheffé) showed that the first block was statistically differ-

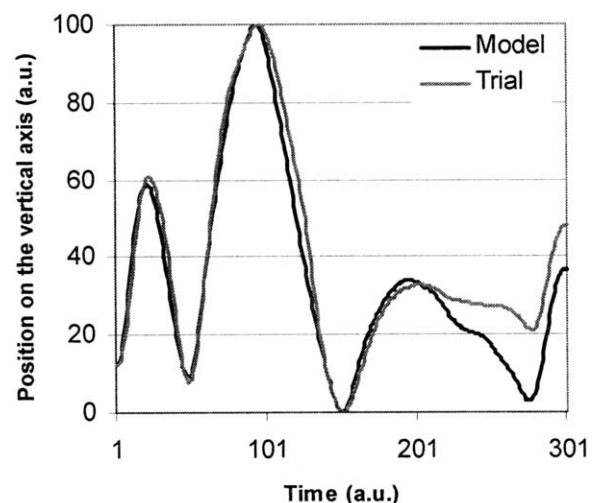


Fig. 1. Plots of the model sequence (black) and of one representative experimental sequence (grey). Time and position along the vertical axis are expressed in arbitrary units (u.a.) after amplitude normalization of the data.

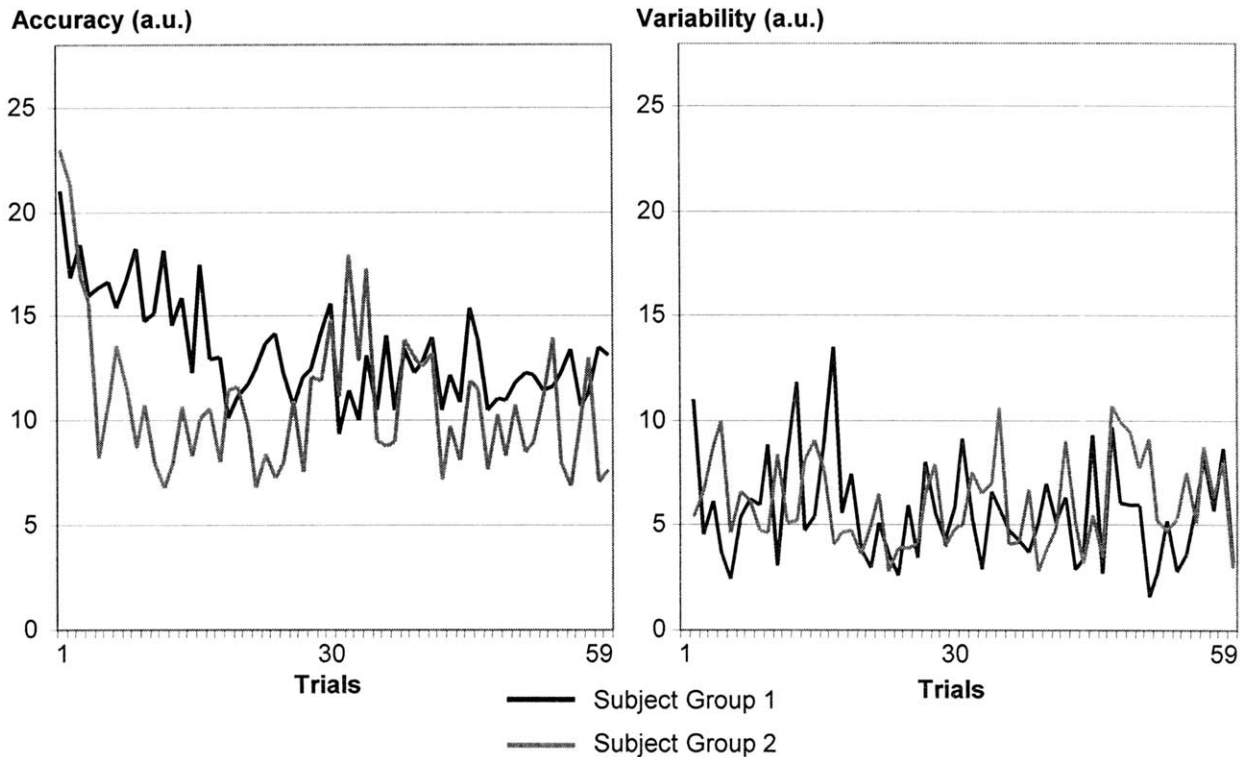


Fig. 2. Accuracy (left) and variability (right) time series of two representative subjects from G1 (black) and G2 (grey).

ent from the others blocks. We also obtained a significant interaction between Groups and Blocks ( $F(11, 110) = 3.49$ ;  $P < 0.003$ ). Post-hoc tests showed that significant improvements in performance occurred earlier in practice for G2 (2nd block) than for G1 (5th block).

Variability data were analyzed by a similar ANOVA 2 (Groups)  $\times$  12 (Blocks) which revealed no significant difference between groups ( $F(1, 10) = 0.91$ ;  $P = 0.36$  ns), a significant Blocks effect ( $F(11, 110) = 5.95$ ;  $P < 0.0001$ ) but not significant interaction between Groups and Blocks ( $F(11, 110) = 1.1419$ ;  $P = 0.33$  ns). Post-hoc comparisons showed that the third first blocks were statistically more variable than the others. These results appeared consistent with those reported in classical motor learning studies.

The accuracy and variability time series of two representative subjects are presented in Fig. 2. Individual series were analyzed using autoregressive integrated moving average procedures [2], which produce iterative equations to model the processes underlying the generation of the time series. Separate analyzes were conducted for the first 30 trials and the last 30 trials.

During the first 30 trials and in the two groups, all accuracy series were satisfactorily fitted by one-term autoregressive models AR(1). These models obeyed the following prediction equation:

$$y_t = \phi y_{t-1} + \epsilon_t \quad (1)$$

where  $\phi$  is the autoregressive coefficient and  $\epsilon_t$  is a random

white-noise process. The coefficient  $\phi$  ranged from 0.890 to 0.973 for G1 and from 0.937 to 0.970 for G2.

During the last 30 trials, in most cases and for both groups, time series analyzes revealed a white noise model, which obeys the following equation:

$$y_t = \mu + \epsilon_t \quad (2)$$

where  $\mu$  is a constant and  $\epsilon_t$  is a random white-noise process. An autoregressive model AR(1) was evidenced, nevertheless, for two subjects in G1.

We assessed the duration of AR(1) process by determining for each subject the trial from which subsequent data points constituted a white-noise process. These analyzes revealed large inter-individual differences, with a minimum of nine trials, and a maximum of 38 trials. We obtained a median of 24 trials for G1, and 17 trials for G2 (grand median = 20 trials). Nevertheless, a Mann–Whitney test did not evidence a significant difference between these medians ( $U = 12$ ,  $P = 0.33$  ns).

Finally, the analysis of variability time series evidenced white noise models for all subjects, over the entire course of the experiment, and whatever the recall conditions.

Analyzes of variance showed that practice led in both groups to an improvement of recall accuracy and a decrease in trial-to-trial variability. These effects appeared quite early in practice, and both variables reached at the end of the first 30 trials a kind of plateau, and were not affected during the last trials by the experimental conditions. The systematic

availability of the model for G1 did not allow further improvement of accuracy or decrease in variability.

Time series of recall performance were analyzed in order to study the ongoing mnemonic activity triggered by this visuomotor task, and to observe the dynamics of the processes underlying the construction of a mental representation during learning. Our primary aim was to provide evidence of a deterministic relationship across trials, hypothesizing that the accuracy of the recalled sequences would reflect the mechanisms that build and structure internal visuomotor representations, and hence the movement-sequence learning process.

The AR(1) model obtained for the first 30 trials suggested that recall performance at time  $t$  was largely determined by performance at time  $t - 1$ . This model points out the short-term historicity of the deterministic inter-trial relationship, which can be summarized as a dependency relationship between two consecutive trials.

Variability in recall performance could arise from multiple sources. In their model, Wing and Kristofferson [11] distinguished two sources of variability: a central variability that could correspond in the present experiment to motor representation, and a peripheral variability corresponding to errors in the execution of the responses. Gilden [4] showed that motor errors were uncorrelated in time, and as such peripheral variability could be considered as a white noise process. Consequently, time dependence in performance series should be related to central variability. In the present case we hypothesize that the short-term historicity was related to the migration process of visuomotor representation. The AR(1) process we evidenced suggests that recall performance over time was not organized, trial after trial, around a kind of internal reference (in which case we should have found a moving average process; see Spray and Newell [9]). The initial trials on the task thus do not seem characterized by the construction and the gradual refinement of a representation of the to-be-executed sequence, but rather by the use of short-term memory traces of the performance achieved on the previous trial. This suggests an exploratory behavior based on progress already made and guided by the goal to be reached [8].

The analyzes of the last 30 trials yielded a completely different process. For most of subjects, the series seemed to fit with a white-noise process, which means that performance was randomly distributed around a constant reference value. This model implies that the recall series has become stationary. The migration process observed on the first set of trials was finished, so one can hypothesize that a stable representation of the sequence has been built in long-term memory and was utilized to produce movements.

It is important to note that for both groups, performance

stabilized at a set distance from the model (with a mean of  $11.01 \pm 1.25$  for G1 and  $11.18 \pm 0.91$  for G2); subjects reached a peak accuracy level that did not improve with trials repetition or with model presentation. This finding should be linked to the previous result showing that the subjects' behavior had lost all historicity. This phenomenon is also consistent with the results of Giraudo and Pailhous [5]. They may be explained both by limitations in the elaborateness of the representation (i.e. its maximum level of accuracy) and by the fundamental variability inherent to the system.

The randomness noted in the series at this stage of the learning process is nevertheless quite surprising. A number of studies (see Gilden [4]) have shown that performance variations in a stable state exhibit characteristics of long-term correlation and self-similarity, and can be modeled as fractional Brownian motion. This type of stochastic process was found in many biological time series and could express a common feature in complex systems. One can hypothesize that such long-term correlation might be found in longer series where recall performance has been stabilized. One could then study consolidation processes, still poorly understood [5], by examining the chaotic nature of variations in recall performance.

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