

A Neural Scheme for Procedural Motor Learning of Handwriting

Rosa Senatore
DIEII - University of Salerno
rsenatore@unisa.it

Angelo Marcelli
DIEII - University of Salerno
amarcelli@unisa.it

Abstract

Handwriting analysis, which requires the detection and examination of distinctive features within the ink traces representing the words, provides a valuable help in several research's fields. In medical field, handwriting analysis provides an useful complement to other clinical investigations in diagnosing many movement disorders, such as Parkinson's disease. In forensics, the examination of particular characteristics of the ink trace allows the expert to evaluate the authenticity of an handwritten text. Handwriting recognition, which allows to optimize the handling of manuscript documents, requires the detection of distinguishing features for interpreting the characters the ink trace represents. Since any phenomenon can be better understood and analyzed when the generative process is known, investigating the process that underlies handwriting might give some guidelines for handwriting analysis. In this respect, we propose a neural scheme, envisaging that performing complex motor sequences, such as handwriting, requires the interaction among the Cortex, Basal Ganglia and Cerebellum.

1. Introduction

Many research areas, from neuroscience to engineering, investigate, from different perspectives and for diverse purposes, the processes that allow humans to efficiently perform skilled movements.

Understanding these processes could provide important insights for many applications, from the design of robotic limbs to the development of new treatments for movement disorders. In handwriting analysis, knowledge of the process underlying handwriting generation might provide further criteria for selecting the most representative features associated to a writer or containing more information about the message (i.e. the word) the ink trace represents, and the way to examine them.

Therefore, it is helpful to understand the processes

involved in generating a complex sequence of movements, such as handwriting, and how different levels of the nervous system interact and contribute to the gradual improvement of motor performance during learning.

Handwriting is a highly skilled and complex motor activity, produced through a perception/action cycle, involving brain areas implicated in attentive vision, learning, and control of several motor subsystems. From a motor viewpoint, handwriting is performed by properly coordinating movements of the lower arm, wrist and fingers [27], which give rise to the sequence of elementary shapes (i.e. the strokes) whose concatenation generates the ink trace representing the characters and, ultimately, the word.

- How does the central nervous system control and coordinate these sequence of elementary movements?
- Which brain areas are involved in learning handwriting? How are handwriting movements represented within these neural structures?
- What is the process that allows adults to write being apparently unaware of the movements they are performing?

In order to address these questions, we propose a new hypothesis about the processes occurring during acquisition and retention of motor skills.

We suggest that the process allowing humans to acquire handwriting (and, more generally, motor skills) follows two distinct phases:

- During the early, fast learning stage, humans learn the spatial sequence associated to the motor task in visual coordinates, i.e. the sequence of points to reach in order to generate the ink trace.
- During the late, automatic phase, the sequence of motor commands in motor coordinates is acquired and comes to be executed as a single behavior.

Accordingly, we propose a neural scheme, comprising the Basal Ganglia, Cerebellum and Cortex, which envisages that the cortex-basal ganglia interaction plays a key role during learning, whereas the cortex-cerebellar interaction is crucial for motor skill retention.

In the next section we illustrate the hypothesis behind the neural scheme here proposed. In section 3 we describe the proposed neural scheme for motor learning. In section 4 we evaluate the neural scheme, comparing the results reported by many studies on motor learning with the predictions provided by the neural scheme. Conclusion and further directions are left to Section 5.

2. A new hypothesis for procedural motor learning

According to the daily experience, a coordinated sequence of "elementary" movements is acquired and executed faster and more accurately the more it is practiced. Indeed, early in learning actions are attention demanding, slow and less accurate, whereas after long-term practice performance becomes quick, movements are smooth, automatic, and can be performed effortlessly, using minimal cognitive resources.

Are there different processes underlying these two phases? What are these processes?

Studies on motor control have shown that selection, execution and learning of movements needed to perform a motor task involve several brain areas and motor subsystems, but their activation and cooperation depend on the kind of movements that are being made and on the effector that is being used [12].

According to these studies, a motor skill is acquired after repeated practice and can be seen as a sequence of elementary actions, combined in the appropriate order to achieve a particular goal. For example, writing cursively is a complex sequential procedure and, on the basis of studies in handwriting generation, the complex movement needed to generate handwriting results from concatenation of elementary movements [17].

Kawato suggested that each elementary motor action is performed following a sensorimotor transformation process in which the location of the target, encoded in trajectory coordinates, is converted into information suitable for the motor system [12] (see Figure 1(a)). However, this process involves a large amount of computation, especially for more complex actions, so it is extremely demanding for the brain to carry out the serial sensorimotor process precisely. Accordingly, the first phase of learning is characterized by slower and attention demanding actions that rely on visual and proprioceptive feedback. The feedback information allows

humans to correct, trial by trial, the trajectory and motor plans, in order to perform the task more efficiently, adopting a coordination and control solution more accurate in terms of the motor production and more economical in terms of the metabolic energy expenditure [25]. Simulating the feedback process in a system that retrieves dynamic information from off-line cursive handwriting has shown that its function improves writing order recovery [22].

After long-term practice of the motor task, performance becomes quick, less metabolic energy is consumed, and the sequence becomes automatic, is characterized by anticipatory movements, and needs little or no thought to be completed. Following these considerations, it can be suggested that when a skill is acquired, the sequence of movements is learned as a single behavior and there is no more need for the visuo-proprioceptive feedback and the sensorimotor transformation (Figure 1(b)).

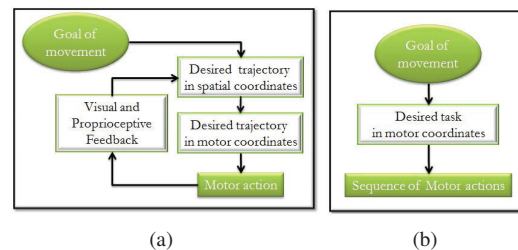


Figure 1. Execution of a novel (a) and well-known (b) sequence of elementary movements.

Indeed, when a child starts learning handwriting by copying letters or words, he attempts several trajectory patterns in order to replicate the same shape of the letters, selecting the points to reach through the visual system, and performing the appropriate sequence of movements through the motor system. During the initial phase of learning, the movements are quite straight and aimed to reach a sequence of points. The executed motor plan is corrected according to the information provided by the visual and proprioceptive feedback, so that the actual trajectory corresponds to the desired one, and the lowest energy is spent by the muscular subsystem involved. As learning proceed, simple point-to-point movements become continuous, curved and smoother, the motor sequence comes to be executed as a single behavior and is performed automatically, using minimal cognitive resources.

There is also strong evidence, supported by the results of several experimental studies on motor learning,

that a given sequence of actions is learned from different perspectives. It has been observed, first by Lashley [14] and then by Hebb [8], that a generic movement, learned with one extremity, can be executed by different effectors. Furthermore, other studies have shown that writing movements learned through the dominant hand could be repeated using different body parts, such as non-dominant hand, the mouth (with the pen gripped by teeth) and foot (with the pen attached to it), even if the subject had essentially no previous experience writing with any of this body parts [18, 29]. Despite the different muscle and skeletal systems used and, even though the movements are not smooth, it can be observed that the writing production follows the same trajectory in all conditions [18] (see Figure 2). The ability to perform the same movement pattern by different muscular systems is called "motor equivalence". It suggests that movements directed to perform a task are stored in the brain in two ways: in an abstract form (effector-independent) related to the spatial sequence of points representing the trajectory plan, and as a sequence of motor commands (effector-dependent) directed to obtain particular muscular contractions and articular movements.

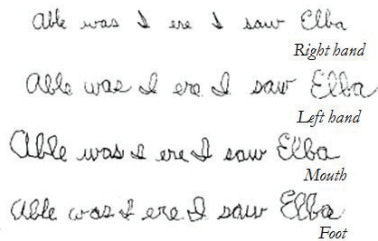


Figure 2. A sentence written by the same writer using different body parts. Adapted from [18].

Other studies on motor learning have shown that when the untrained hand is used to perform a given sequence, learned with long-term practice with the other hand, performances are poor, but this is not true for a newly learned sequence [19], supporting the hypothesis that early in learning the execution of the motor task is more based upon the trajectory plan (effector independent), whereas late in learning upon the sequence of motor commands (effector-dependent).

Accordingly, we suggest that handwriting learning follows two distinct phases, in which two different processes take place, and that early in learning, handwriting skill (or, in general, a motor skill) is acquired as a sequence of spatial coordinates converted into motor

commands, while as learning proceeds, the sequence of motor commands is acquired and it comes to be executed as a single behavior.

3. A neural scheme for procedural motor learning

Execution of voluntary movements requires the interaction between nervous and musculoskeletal systems, involving several areas, from the higher cortical centers to the motor circuits in the spinal cord [11].

In seeking to understand all the breadth and facets of motor learning, many researchers have used different approaches and methods, such as genetic analysis, neuroimaging techniques (such as fMRI, PET and EEG), animal models and clinical treatments (e.g. drugs administration and brain stimulation). These studies have provided a large body of knowledge that has led to several theories related to the role of the central nervous system in controlling and learning simple and complex movements. According to the results reported by neuroimaging and experimental studies on motor learning, several cortical and subcortical structures, including the basal ganglia, cerebellum, and motor cortical regions, are thought to be critical in different stages and aspects in the acquisition and/or retention of skilled motor behaviors. Several studies have investigated the functional anatomy and the cerebral plasticity associated with motor skill learning using brain image techniques in healthy subjects to track the time course of cerebral activation during extended practice of a motor sequence. With the same aim, other studies analyzed motor performances of patients affected by neurodegenerative disease or cerebral damage during the execution and acquisition of a motor task.

Results of an fMRI study [20] reported the involvement of the parietal cortex in general, and posterior parietal cortex and occipitotemporal junction in particular, in the representation of written letter forms. Other neuroimaging studies suggest that a novel sequence of movements is initially mapped to form an internal representation of the sequence that is progressively encoded and refined subcortically (in the basal ganglia and in the cerebellum) as performance improves [26].

The imaging data reported by other studies on motor learning support the notion that distinct regions of the basal ganglia participate in different stages of learning. These studies report increased activity within the striatum (the input nucleus of the basal ganglia), in particular within the associative striatum and sensorimotor striatum early and late in learning, respectively. However, although there is solid evidence that the initial learning of many skills depends on the striatum, there

are contrasting results in the literature regarding to the role of the sensorimotor striatum in automatic responding [28]. These results sustain the hypothesis that the basal ganglia play an important role in the initial stage of learning, whereas it is not well-established their importance in the final stage of learning.

With regard to the cerebellum, many studies report increased activity within the cerebellar cortex during learning, and increased activity within the dentate nucleus (an output nucleus of the cerebellar circuitry) until automaticity is achieved. A detailed review of the imaging studies whose results are here cited can be found in [21].

According to these results, we propose a neural scheme, based on the hypothesis that acquiring new motor skills requires two phases, in which two different processes occur.

The neural scheme for motor learning is shown in Figure 3 and incorporates the parietal and motor cortex, basal ganglia and cerebellum.

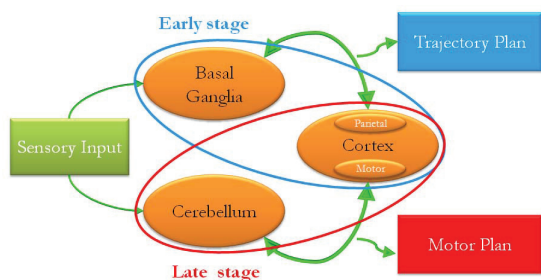


Figure 3. Neural scheme of the model for procedural motor learning.

Sensory information is provided by an input module (sensory input in the figure) to the cerebral cortex, basal ganglia and cerebellum. The parietal association cortex releases signals that specify the position of targets in extrapersonal space (according to the studies conducted by Andersen and Zipser [1] and Rijntjes [20]). Therefore, the basal ganglia, interacting with the parietal cortex, select the next target point in the sequence. In turn, parietal cortex sends this information to the cerebellum that, interacting with the motor cortex, selects the appropriate motor command.

This model fits the hypothesis presented in section 2, according to which motor learning follows two distinct phases. During the early phase of learning, the model learns the spatial sequence in visual coordinates (i.e. the sequence of points to reach in order to realize the motor task) through the interactions between the basal ganglia and the parietal cortex. The spatial se-

quence is then converted into motor commands through the interactions of the cerebellum and the motor cortex. Therefore the cerebral cortex, basal ganglia and cerebellum initially would work in parallel. The basal ganglia, through the associative striatum, are involved in the acquisition of the spatial sequence and the cerebellar cortex starts working to acquire the motor sequence. As learning proceeds, the sequence of motor commands in motor coordinates is acquired and stored in the dentate nucleus.

Consequently, it would be expected that, early in learning, task performance is more dependent on the procedural knowledge maintained by the cortex-basal ganglia system and, after a long-term practice, task performance is more dependent on the motor sequence maintained by the cortex-cerebellar system.

4. Discussion and Conclusions

The proposed hypothesis for procedural motor learning envisages that the basal ganglia, interacting with the parietal cortex, select the next target point within the trajectory plan associated to the motor task. Looking at the neural scheme, whether basal ganglia dysfunction would impair learning of the correct sequence of target points, then the cerebellum would be provided (by the parietal cortex) with wrong information about the trajectory plan. This would cause the cerebellum to select wrong motor commands. Instead, late in learning, basal ganglia dysfunction should not influence the execution of the motor behavior since the sequence of motor commands has been acquired within the cerebellum .

Experimental support to this hypothesis comes from the observation that Parkinson’s patients (a disease affecting basal ganglia function) are able to perform automatic motor responses elicited by a stimulus, but they have difficulties in executing novel motor actions [13]. Indeed, it has been shown that dopamine, a neurotransmitter that modulates basal ganglia activity (that is lacking in Parkinson’s patients), critically mediates the acquisition and expression of a behavior during the initial stage of learning, whereas it plays a diminishing role in executing well-learned behaviors [9, 24].

Our hypothesis also envisages that the cerebellum, interacting with the motor cortex, is involved in selecting the appropriate motor command and that, late in learning, the sequence of motor commands is stored in the dentate nucleus. Indeed, as reported in [15], the inactivation of the dentate nucleus would not result in a loss of performance in learning of a new sequence, whereas after a long-term practice loss of the dentate nucleus function would affect the performance. We speculate that dentate inactivation during the early

stage of learning does not affect performance because in the early phase of learning the procedural knowledge is maintained by the cortex-basal ganglia mechanism. Instead, when the motor sequence is acquired within the dentate, the execution of the motor sequence is more dependent on the cortex-cerebellar mechanism, therefore dentate inactivation during this stage affects performance. Furthermore, results reported in several studies suggest that the cortico-cerebellar system is involved in motor adaptation, especially in the late stage of learning and in the retention phase [3]. In a motor adaptation task the participants are required to learn how to adapt their movements according to some external changes, artificially imposed by the experimenter. The study of Smith and Shadmehr [23] on motor adaptation showed that patients affected by cerebellar degeneration were impaired in adapt their movements. On the basis of their results, we speculate that in motor adaptation task, when the relation between movements of the joystick and cursor is altered, knowledge of the sequence of points to reach is not sufficient to efficiently perform the task, but it is also necessary to acquire the sequence of motor commands. Further evidence about the plausibility of our hypothesis comes from the anatomical two-way path between basal ganglia and cerebellum, found by Strick and colleagues [2, 10]. In the former work [10], they found a disynaptic pathway that links the dentate nucleus with the sensorimotor striatum. Particularly, they found that projection from the dentate to the striatum connects with medium spiny neurons composing the "indirect" pathway of basal ganglia, whose role consists in suppress behavior. In the latter work [2] they found a disynaptic pathway that links the subthalamic nucleus (a nucleus that modulates basal ganglia output) with the cerebellar cortex, and that this connection is topographically organized. These connections are consistent with the neural activation paths found by the imaging studies and our hypothesis. Accordingly, we suggest that since the subthalamic nucleus is more active in the early stage of learning, it would provide the cerebellar cortex with further excitatory input that decrease as the spatial sequence is acquired. This, in turn, would reduce activity within the dentate nucleus (since it receives an inhibitory connection from the cerebellar cortex). In the late stage of learning, when the sequence of movements is acquired as a single behavior and, at the same time, the activity in the dentate nucleus increases, its activation provides an excitatory input to the sensorimotor striatum, and in particular to the indirect pathway (in keeping with the imaging data that show increased activity within the sensorimotor striatum during late stage of learning). This pathway would exclude the function of basal ganglia in selecting the next spatial

target in the ordered sequence, because the sequence of motor commands is already acquired as a single behavior and released by the cerebellum.

A model for handwriting learning and generation that incorporates basal ganglia and cerebellum has also been proposed by Grossberg and Paine [7]. The hypothesis behind the model is that the cerebellum acquires the timing of muscle synergy activations in handwriting, whereas the basal ganglia control volitional speed and size of the trajectory. The model output fits the human data, showing that handwriting movements are initially straight and guided by the visual feedback, while are guided by memory and become smooth and continuous after learning. However, since the model mainly addresses the role of the cerebellum in handwriting learning, it does not explain how basal ganglia dysfunction impairs initial learning, as reported by several studies [4, 16, 9, 24, 13].

We have evaluated the neural scheme (and the hypothesis behind it) through a computational model that incorporates the key features of these brain areas in an integrated functional network [21]. The anatomical, physiological and biological of the basal ganglia are implemented as in [5, 6].

In the model, we have simulated basal ganglia and cerebellar damage in different learning stages.

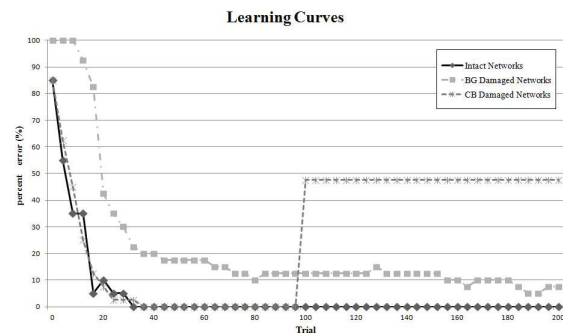


Figure 4. Learning curves in three different conditions: intact networks, basal ganglia damaged networks, and cerebellar damaged networks. Results are averaged over 25 networks for each condition.

Obtained results, reported in Figure 4, show that the basal ganglia play a key role in acquiring a novel motor skill, whereas the cerebellum is crucial for motor skill retention. Indeed, in intact networks, the error rate decreases to zero, whereas basal ganglia damaged networks are unable to learn a novel motor task. Simulated cerebellar damage after learning (i.e. after 100 trials)

impairs the network's ability to perform a pre-learned motor task.

Our results also provided novel predictions about the role the basal ganglia and cerebellum in motor function, gaining further understanding of the functional dynamics of information processing within these neural structures in normal as well as in diseased brains [21]. These results motivates further investigations of their interactions.

References

- [1] R. A. Andersen and D. Zipser. The role of the posterior parietal cortex in coordinate transformations for visual-motor integration. *Canadian Journal of Physiology and Pharmacology*, 66:488–501, 1988.
- [2] A. C. Bostan, R. P. Dum, and P. L. Strick. The basal ganglia communicates with cerebellum. *Proceedings of the National Academy of Sciences*, 107:8452–8456, 2010.
- [3] J. Doyon, V. Penhune, and L. G. Ungerleider. Distinct contribution of the cortico-striatal and cortico-cerebellar systems to motor skill learning. *Neuropsychologia*, 41:252–262, 2003.
- [4] J. Doyon and L. G. Ungerleider. *Neuropsychology of Memory*, chapter Functional anatomy of motor skill learning, pages 225–238. Guilford Press, 2002.
- [5] M. J. Frank. Dynamic dopamine modulation in the basal ganglia: a neurocomputational account of cognitive deficits in medicated and nonmedicated parkinsonism. *Journal of Cognitive Neuroscience*, 17(1):51–72, 2005.
- [6] M. J. Frank. Hold your horses: a dynamic computational role for the subthalamic nucleus in decision making. *Neural Networks*, 19:1120–1136, 2006.
- [7] S. Grossberg and R. W. Paine. A neural model of cortico-cerebellar interactions during attentive imitation and predictive learning of sequential handwriting movements. *Neural Networks*, 13:999–1046, 2000.
- [8] D. O. Hebb. *The organization of behavior: a neuropsychological theory*. Wiley, New York, 1949.
- [9] J. C. Horvitz, W. Yung Choi, C. Morvan, Y. Eyny, and P. D. Balsam. A 'good parent' function of dopamine: transient modulation of learning and performance during early stages of training. *Annals of the New York Academy of Sciences*, 1104:270–288, 2007.
- [10] E. Hoshi, L. Tremblay, J. Feger, P. L. Carras, and P. L. Strick. The cerebellum communicates with the basal ganglia. *Nature Neuroscience*, 8(11):1491–1493, 2005.
- [11] E. R. Kandel, J. H. Schwartz, and T. M. Jessel. *Principles of Neural Science*. McGraw-Hill, 2000.
- [12] M. Kawato. Internal models for motor control and trajectory planning. *Current Opinion in Neurobiology*, 9:718–727, 1999.
- [13] H. I. Krebs, N. Hogan, W. Hening, S. V. Adamovich, and H. Poizner. Procedural motor learning in Parkinson's disease. *Experimental Brain Research*, 141:425–437, 2001.
- [14] K. Lashley. Basic neural mechanisms in behavior. *Psychological Review*, 37:1–24, 1930.
- [15] X. Lu, O. Hikosaka, and S. Miyachi. Role of monkey cerebellar nuclei in skill for sequential movement. *Journal of Neurophysiology*, 79:2245–2254, 1998.
- [16] M. G. Packard and B. J. Knowlton. Learning and memory functions of the basal ganglia. *Annual Review of Neuroscience*, 25:563–593, 2002.
- [17] R. Plamondon and S. N. Srihari. On-line and off-line handwriting recognition: A comprehensive survey. *IEEE transaction on PAMI*, 22:63–84, 2000.
- [18] M. H. Raibert. *Motor control and learning by the state space model*. Cambridge: Artificial Intelligence Laboratory, MIT, 1977.
- [19] M. K. Rand, O. Hikosaka, S. Miyachi, X. Lu, and K. Miyashita. Characteristic of a long-term procedural skill in the monkey. *Experimental Brain Research*, 118:293–297, 1998.
- [20] M. Rijntjes, C. Dettmers, C. Buchel, S. Kiebel, R. Frackowiak, and W. C. A blueprint for movement: functional and anatomical representations in the human motor system. *Journal of Neuroscience*, 19(18):8043–8048, 1999.
- [21] R. Senatore. *The role of Basal Ganglia and Cerebellum in Motor Learning: A computational model*. PhD Thesis, University of Salerno, 2012.
- [22] R. Senatore, A. Santoro, and A. Marcelli. From motor to trajectory plan: A feedback system for writing order recovery. *Human Movement Science (under review)*, 2011.
- [23] M. A. Smith and R. Shadmehr. Intact ability to learn internal models of arm dynamics in Huntington's disease but not cerebellar degeneration. *Journal of Neurophysiology*, 93:2809–2821, 2005.
- [24] S. L. Smith-Roe and A. E. Kelley. Coincident activation of NMDA and dopamine D1 receptors within the nucleus accumbens core is required for appetitive instrumental learning. *Journal of Neuroscience*, 20:7737–7742, 2000.
- [25] W. A. Sparrow and K. M. Newell. Metabolic energy expenditure and the regulation of movement economy. *Psychonomic Bulletin and Review*, 5(2):173–196, 1998.
- [26] B. A. Sweet, J. L. Contreras-Vidal, B. Rasmus, and A. Braun. Neural substrates of graphomotor sequence learning: A combined fMRI and kinematic study. *Journal of Neurophysiology*, 103(6):3366–3377, 2010.
- [27] A. J. W. M. Thomassen and T. H. L. Constancy in stationary and progressive handwriting. *Acta Psychologica*, 54:179–196, 1983.
- [28] R. S. Turner, K. McCairn, D. Simmons, and I. Bar-Gad. *The basal ganglia VIII (Advances in behavioral biology, vol. 56)*, chapter Sequential motor behavior and the basal ganglia, pages 563–574. Springer, 2005.
- [29] A. M. Wing. Motor control: mechanisms of motor equivalence in handwriting. *Current Biology*, 10:245–248, 2000.