A Multi-disciplinary Approach to the Investigation of Aspects of Serial Order in Cognition*

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Abstract:

Serial order processing or Sequence processing underlies many human activities such as speech, language, skill learning, planning, problem solving, etc. Investigating the neural bases of sequence processing enables us to understand serial order in cognition and helps us building intelligent devices. In the current paper, various cognitive issues related to sequence processing will be discussed with examples. Some of the issues are: distributed versus local representation, pre-wired versus adaptive origins of representation, implicit versus explicit learning, fixed/flat versus hierarchical organization, timing aspects, order information embedded in sequences, primacy versus recency in list learning and aspects of sequence perception such as recognition, recall and generation. Experimental results that give evidence for the involvement of various brain areas will be described. Finally, theoretical frameworks based on Markov models and Reinforcement Learning paradigm will be presented. These theoretical ideas are useful for studying sequential phenomena in a principled way.

1.0 Introduction

"… the coordination of leg movements in insects, the song of birds, the control of trotting and pacing in a gaited horse, the rat running the maze, the architect designing a house, the carpenter sawing a board present a problem of sequences of action …".

Karl Lashley (1951), "The Problem of Serial Order in Behavior".

Serial order in behaviour has been studied for a long time. Serial order processing or Sequence processing is a key issue in many areas of cognitive science such as auditory perception, visual perception (three dimensional object recognition), speech perception, language, goal directed planning and problem solving. Investigating the neural bases of sequence processing enables us to understand serial order in cognition and helps us building intelligent devices. In the following section the serial and parallel aspects of cognition are clarified using an example from the domain of face perception.

1.1 Serial versus Parallel Aspects of Cognition

If face perception were to be a parallel process we would apprehend various features of the face at once and as a whole. On the contrary, if perception were to be a serial process, we would attend to various features sequentially one after the other.

Yarbus (1967), in a classic experiment, monitored subjects' eye movements as they viewed portraits. In figure 1, the picture on the right shows the trace of the gaze of a subject exploring the portrait on the left. It was observed that though subjects reported apprehending the portrait as a whole, their eye movements revealed a different story. During the process of perceiving the face, observer's attention moved from one point of

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fixation to another. By analyzing the distribution of points of fixation, the duration of fixation and the distinctive cyclic pattern of examination, Yarbus (1967) concluded that the subjects made saccadic eye movements fixating *successively* at the most informative parts of the image. Thus these observations point out that underlying an apparently parallel process of face perception, there is a serial oculomotor process. This example is presented to clarify the meaning of serial and parallel processes and also to point out that many cognitive phenomena have both the aspects.

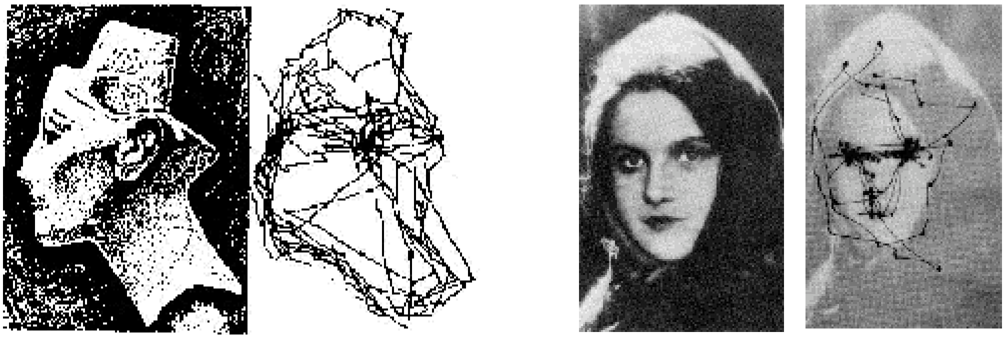


Figure 1: Sequential Aspect of Face perception. A trace of the saccadic eye movements of a subject is shown on the right hand side image while the subject is looking at the portrait shown on the left hand side (Adapted from Yarbus, 1967).

2.0 Issues related to serial order

In the following sections a detailed discussion of several issues related to serial order is presented. The issues discussed are the origin of sequential behaviour in humans, possible representation schemes available, the organization of sequences, the order and timing of individual elements of a sequence, the learning modes, stages and strategies applicable for sequence learning and the issues in sequence perception.

2.1 Origins

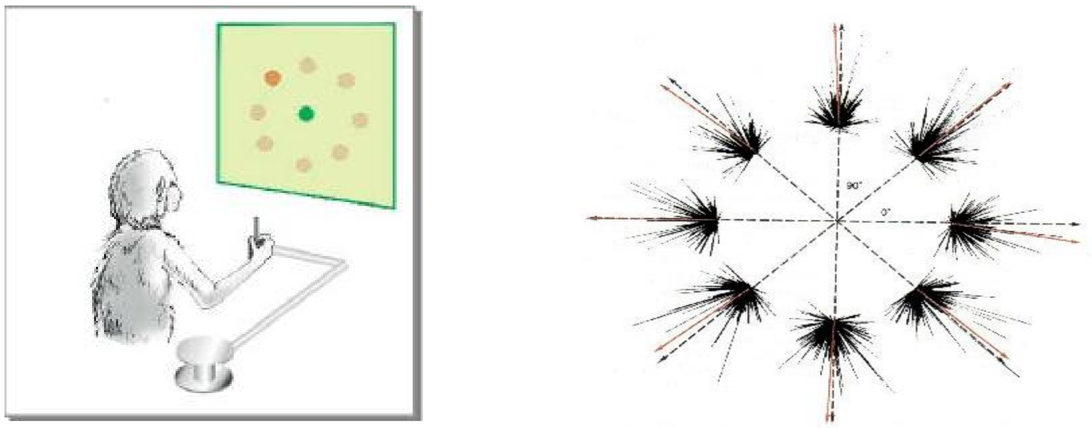
There are broadly two classes of origin for human sequential behaviour — one is evolutionary and the other is through learning. A variety of natural sequential patterns or ritualistic behaviours can be seen in many species including humans. Some examples are the grooming movements in rats, locomotion, mastication, rhythmic respiratory movements, etc in humans. Many species apart from humans are also capable of acquiring sequential behaviours via instrumental conditioning.

Berridge and Whishaw (1992) have studied ritualistic grooming movements in rats. They demonstrated a crucial role for the neostriatum in exhibiting species-specific (genetic or pre-wired) sequencing behaviours in rats. On the other hand, examples of learned (adaptive) behaviour include speech, language, skills etc. Diamond (1996) studied performance of infants and monkeys on Delayed Response (DR) tasks that assess the Working Memory (WM) capacity. These tasks require the subjects to hold information for a length of time in the mind even in the absence of external cue. The subject initially watches the experimenter hide a desired object in one of two identical wells. After a brief delay during which the wells are hidden from the view, the subject is allowed to reach out and retrieve the hidden object. Infants of 7½–9 months fail delayed response under the same conditions and in the same ways as do monkeys with lesions of the Dorsolateral Prefrontal Cortex. It is therefore suggested that improved performance on this task is an index of maturation of frontal cortex function. Diamond (1996) proposed that maturation of the prefrontal cortex might make possible the age-related developmental progression of human infants on working memory tasks. These studies give clues to the adaptive origin of some behavioural sequences.

Thus, some behavioural sequences have pre-wired origin, while many more are learned. It has also been proposed that propensity to engage in complex sequential activities, such as imitation is a precursor to high level behaviours such as empathy, mental simulation (for example see Arbib and Rizzolatti 1996).

2.2 Representation

In the following we will present evidence for both local and distributed representation of human movements. Georgopoulos and colleagues (1989) have shown that reaching movements of the arm are represented not by single neurons, but by the combined activity of a large population of cells in the motor cortex of the brain. They recorded from 568 cells in monkey cortex while the monkey performed reaching arm movements as shown in figure 2(a). They found that each individual cell responded best for arm movements in a given direction, and its response gradually tailed off for arm movements in adjacent directions as shown in figure 2(b). They argued that the direction of movement is represented in the motor cortex by a population vector, which rotated when the monkey intended to move a lever in a rotated direction, prior to movement.



(a) (b)

Figure 2: **Distributed Representation of Arm Movements**. **(a)** Monkey trained to move in one of the eight radial directions. **(b)** Neuronal population vectors representing each of the eight radial movements (Adapted from Georgopoulos et al.,1989)

Tanji and Shima (1994) have found a group of cells in the cerebral cortex of monkeys whose activity is exclusively related to a sequence of movements performed in a particular order – hinting at a local representation for sequences. Two monkeys were trained to perform three movements (Push, Pull or Turn a manipulandum) in four different orders. Before each movement, monkeys waited for a tone that served as a movement trigger. During learning phase, the correct movement required was indicated by a Green (Push), Yellow (Pull) or Red (Turn) light. After five learning trials the animals performed the sequence from internal memory in the absence of external visual cues. It was observed that the cells in the supplementary motor area (SMA) were active while the animal was waiting to perform a motor sequence of turn-pull-push (figure 3b). But such activity was not observed while the monkey was waiting to perform a different sequence of turn-push-pull (figure 3a).

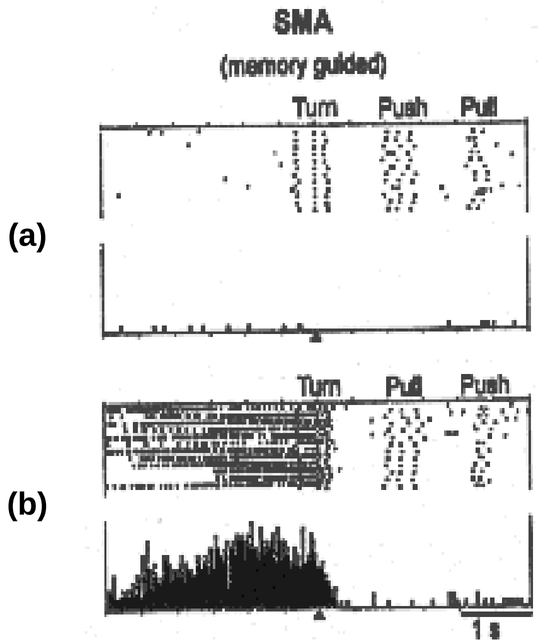


Figure 3: **Local Representation of Arm Movement Sequences. (a)** Low activity found in an SMA neuron tuned to Turn-Pull-Push when the monkey was performing a different sequence, Turn-Push-Pull. **(b)** The same neuron exhibits high sequence-specific activity when the monkey performed Turn-Pull-Push sequence (Adapted from Tanji and Shima, 1994)

While studies of Georgopoulos have indicated a distributed representation for individual arm movements, Tanji's studies suggest a possible local representation for sequences of movements.

2.3 Organization

Internal organization of behavioural sequences can be either linear (flat) or nonlinear (hierarchical). Lashley (1951) argued that the apparent linear serial order in action outputs concealed an underlying hierarchical structure that enabled an internal parallel access to the constituents of a sequence. Dawkins (1976) also proposed that hierarchical organization is pivotal to understanding the evolution of behaviour, arguing by analogy with many other cases in developmental and neural biology which had already been found to be hierarchical, and on grounds of efficiency. Hierarchical organizations of control, he showed, are easier than linear ones to repair when they fail, allow the economy of multiple access to common subroutines, and combine efficient local action at low hierarchical levels while maintaining the guidance of an overall structure. In human behaviour, hierarchical structuring has long been argued to be essential for many acquired skills, such as language, problem solving and everyday planning (Chomsky, 1957; Newell, Shaw and Simon, 1958; Miller, Galanter and Pribram, 1960; Newell and Simon, 1972). The notion of chunking has also been studied in the context of hierarchical organization (for example, Wickelgren, 1969 and 1999; Mackay, 1982)

2.4 Order

The order of storage of sequence of entities is another issue to be considered in serial order. The items could be stored in the order they are encountered, i.e., the first items are stored with more emphasis than the last items or the other way round. If the first items are stored more strongly and recalled more easily, then the process is said to have *primacy effect*. On the other hand, if the last items are emphasized more and retrieved with ease, then the process is said to possess *recency effect*. Figure 4 shows a Serial Learning Curve that is typically seen in list learning tasks. This curve reveals that subjects recall words presented at the beginning and the end of a list better than words presented in the middle. It is proposed that the items at the beginning may take advantage of the long-term memory laid down by more frequent rehearsals. The items at the end are easy to recall because they are active in working/short term memory (see for example the discussion of Serial List Learning in Grossberg 1969). Further, as far as working memory (Baddeley, 1986) is concerned, Miller (1956) proposed 7±2 constituents as its limit. Any theory of serial order has to address these order issues also need to keep in mind the limitations to working memory capacity.

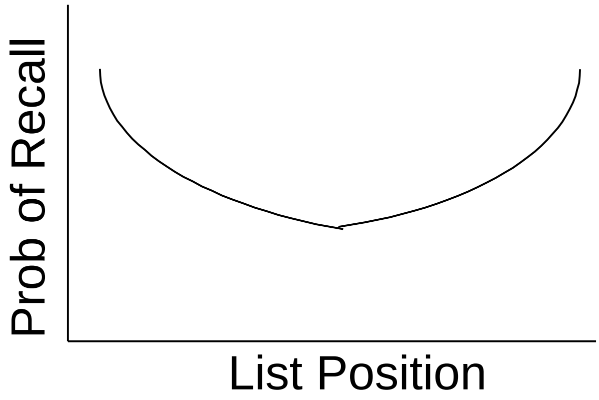


Figure 4: **Serial Position Curve**. The curve shows the relationship between the List Position of an item and the associated Probability of Recall. The curve depicts both the Primacy and Recency effects.

2.5 Timing

In the previous sections, we presented issues related to *what* type of representation and *which* order of storage but the question of *when* to perform successive items is also important. The relative timing of the elements of a sequence may be fixed or variable. For example, in a musical piece or poetry apart from the order of items the relative timings are also important. In contrast, in standard prose-like text timing is not an issue. Similarly, the overall speed of execution may also be fixed or variable. The important point here is that if relative timings are variable, then one needs to think of the storage and retrieval scheme for these along with the scheme for items themselves.

2.6 Learning

In this section, we will discuss different aspects related to learning, such as implicit and explicit learning modes, stages in learning, and learning strategies.

2.6.1 Learning modes

Learning of serial order may be operating in one of the two modes – explicit learning mode or implicit learning mode. Explicit learning includes conscious attempts to construct a representation of the task; directed search of memory for similar or analogous task relevant information; and conscious attempts to derive and test hypotheses related to the structure of the task (for example, Anderson 1982). This type of learning has been distinguished from alternative modes of learning, termed implicit learning, in which task relevant information is acquired automatically and without conscious awareness of what is being learnt (for example, Cleeremans 1993).

2.6.2 Learning Stages

It is a common observation that when a skill, involving sequence of entities, is being acquired, we need to be more attentive in the initial phase; however, during the later, more automatic phase, attention can be engaged in other tasks. Fitts (1964) proposed a framework for skill acquisition that included two major stages in the development of a cognitive skill: a declarative stage in which facts about the skill domain are interpreted and a procedural stage in which the domain knowledge is directly embodied in procedures for performing the skill.

2.6.3 Learning Strategies

We can distinguish learning strategies broadly into two main categories: supervised and unsupervised, based on whether feedback was provided or not. In supervised learning, we assume that the teacher provides the desired response at each instant of time. In a variation of supervised learning called reinforcement learning, a coarse feedback indicating the quality of the output is provided without specifying the desired response. In learning without supervision, the desired response is not known. Thus explicit error information cannot be used to improve behaviour in unsupervised learning. It has been proposed that a different set of brain areas is associated with different learning strategies (Doya, 1999).

2.7 Perception

A potential theory of Serial Order needs to deal with various sequence perception problems organized broadly into two categories: sequence recognition and sequence recall / generation. These problems can be stated formally as shown below (Sun, 2000 and 2001).

1) Recognition: Given a sequence $s_i, s_{i+1}, \ldots, s_k$; recognition problem involves determining if the given sequence is legitimate or not.

$$s_i, s_{i+1}, \ldots, s_k \rightarrow \text{yes or no, where } 1 \leq i \leq k \leq \infty$$

2) Recall / Generation: Given a sequence $s_i, s_{i+1}, \ldots, s_k$; recall or generation problem involves generating or recalling the next item s_{k+1}.

$$s_i, s_{i+1}, \ldots, s_k \rightarrow s_{k+1}, \text{ where } 1 \leq i \leq k \leq \infty$$

3.0 Brain Areas sub-serving Aspects of Serial Order

In this section, we give a brief introduction to various areas of the brain and present results from our own and other experimental efforts investigating sequential skill acquisition.

3.1 Introduction to Brain Areas

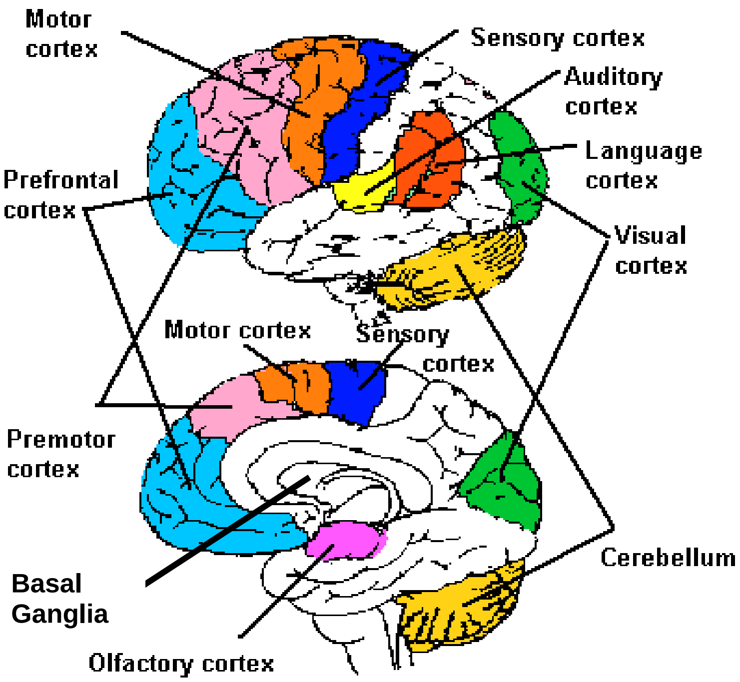


Figure 5: Gross Areas of the Human Brain. Top Picture is the Surface view and the Bottom one is the Sectional view.

As shown in figure 5, the cerebrum sits at the topmost part of the brain and is the source of intellectual activities. It holds memories, allows planning, enables imagination and thinking. It allows recognition of friends, reading books and playing games. The Prefrontal cortex is the seat of thinking, planning and central executive functions. The Visual cortex performs visual perception and processing. The Motor cortex is an area at the rear of the frontal lobes that controls voluntary movements. The Sensory cortex registers and processes body sensations. Areas of the cerebral cortex that are not involved in primary motor or sensory functions are called Association areas. They are involved in higher mental functions such as learning, remembering, thinking, and speaking. The function of the Cerebellum involves coordination of voluntary movement, balance and equilibrium, and some memory for reflex motor acts. The Basal ganglia are involved in initiation and control of movements. A specialized part of the Premotor cortex, called Broca's areas is involved in the motor aspects of language and a special part of the auditory cortex, called Wernicke's area is involved in the sensory aspects of language (Heimer, 1983).

3.2 Brain Areas involved in Serial Order

The fundamental idea that memory is not a single entity but consists of several separate entities that depend on different brain systems has been discussed by Squire and Zola-Morgan (1996). The key distinction is between the capacity for conscious recollection of facts and events (declarative memory) and a heterogeneous collection of nonconscious learning capacities (nondeclarative memory) that are expressed through performance and that do not afford access to any conscious memory content. Procedural memory is part of the nondeclarative category. As shown in figure 6, the area specifically proposed for procedural memory is the Striatum. Berridge and Whishaw (1992) showed that lesions of the precentral cortical areas or of other cortical areas did not affect the performance of ritualistic behavioural sequences in rats. On the other hand lesions of the neostriatum, which receives inputs from the cerebral cortex, impaired the performance thereby implicating a role for striatum in behavioural sequences. Curran (1995) and Clegg et al. (1998) also summarized evidence for striatal involvement in sequence learning based on experiments involving implicit learning tasks.

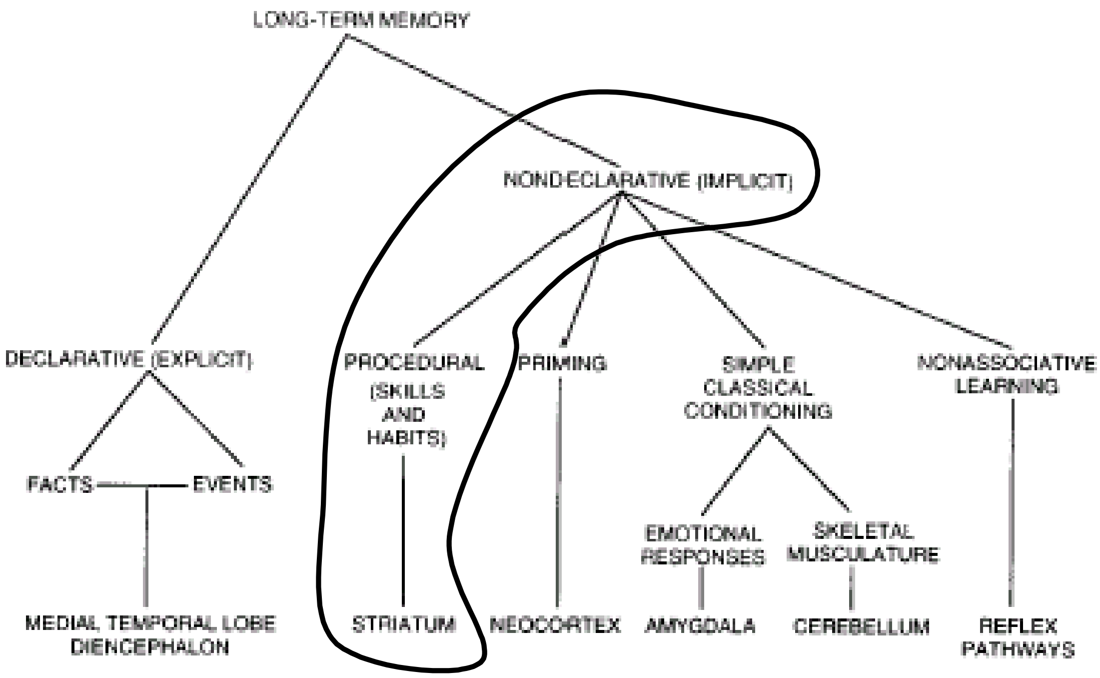


Figure 6: Taxonomy of Long-Term Memory. Brain systems associated with different categories of long-term memory are shown and the category for Procedural memory is highlighted specifically (Adapted from Squire and Zola-Morgan, 1996).

Studies by Jeuptner et al (1997) have shown that as learning progressed in a finger-movement learning task, brain activation shifted from the anterior to the posterior parts both in the neocortex and the sub-cortical structures. Our behavioural (Bapi, Doya & Harner, 2000) and functional magnetic resonance imaging (fMRI) experiments investigated different aspects of procedural memory such as Representation (Bapi, Graydon & Doya 2000), Complexity (Miyapuram et al. 2001), Learning Mode, etc. using a finger-movement sequence learning task. Figure 7 describes a modular view of the finger-sequence learning task. We proposed possible cortical localization of various modules and mappings that subjects use while practicing a set of finger movements in response to visual stimuli. In early stages of learning this task, subjects may follow a long route, in which the response is mediated by a Visuo-Spatial Mapping followed by a Spatial-Motor Mapping. While in the late stages of learning this task, subjects may follow a short route, where they utilize a direct Visuo-Motor mapping. Further, we hypothesised that there are two sequence representations, effector independent in visual/spatial coordinates and effector dependent representation in motor coordinates.

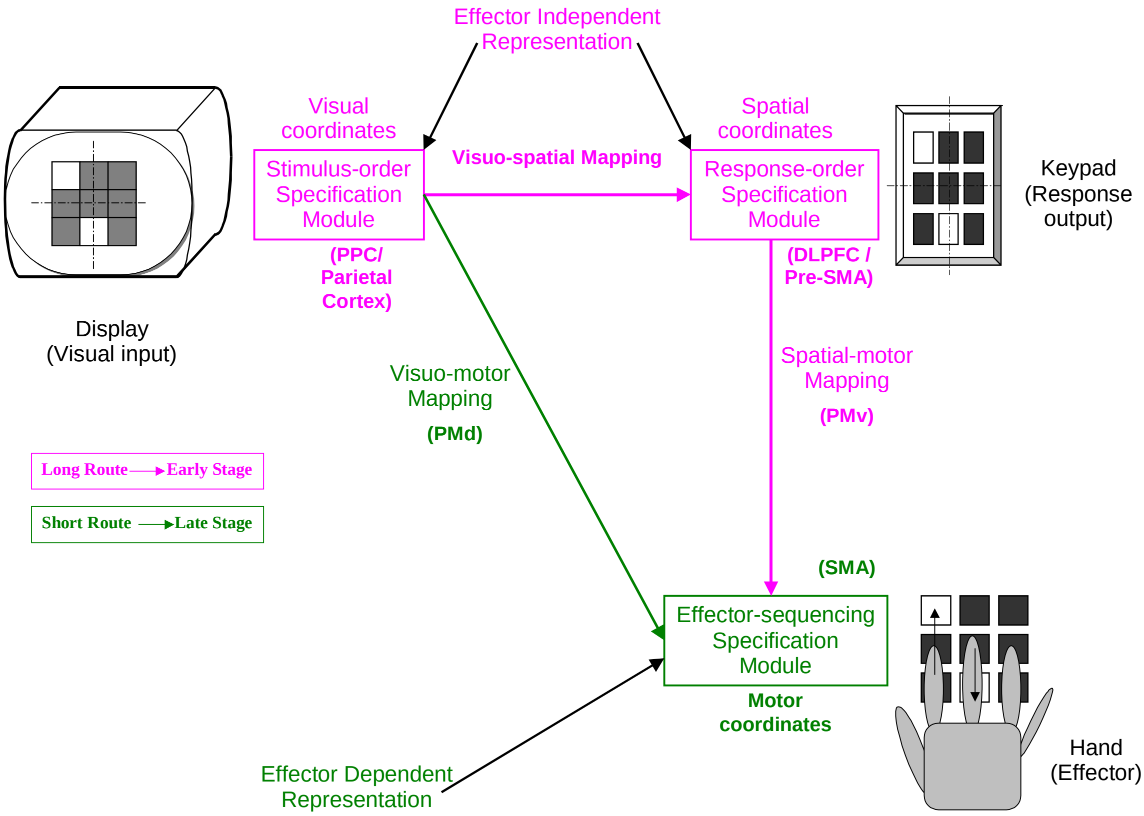


Figure 7: Modular View of the Finger-Sequence Learning Task. Acquisition of two representations – effector independent and dependent, along two different routes – long and short and the brain areas that may be involved in the learning process are shown (Adapted from Bapi, Doya & Harner, 2000).

The brain areas proposed are: the Posterior parietal cortex for visual sequence representation; the Dorsolateral prefrontal cortex and the pre-Supplementary motor area for response sequence representation and the Primary motor area and the Supplementary motor area for motor sequence representation (Bapi, Doya & Harner, 2000).

4.0 Theoretical Framework

Sequencing is an essential aspect of animal and human behaviour. Figure 8 depicts the efforts involved in the scientific endeavour towards understanding serial order or sequencing. There are two main efforts in this direction – one is experimentation and the other is building theoretical framework and undertaking computational modelling work. The former effort enables understanding the behavioural and neural correlates of sequencing. The latter effort engenders functional understanding. It is very difficult, if not impossible, to gain complete functional understanding of a cognitive phenomenon by a pure empirical approach. Similarly, a pure theoretical or modelling approach will run the risk of lacking biological realism and relevance. Hence, the main thesis of this paper is that both empirical and modelling efforts are of utmost importance and that they reinforce each other. The other point emphasized here is that these efforts must go hand-in-hand.

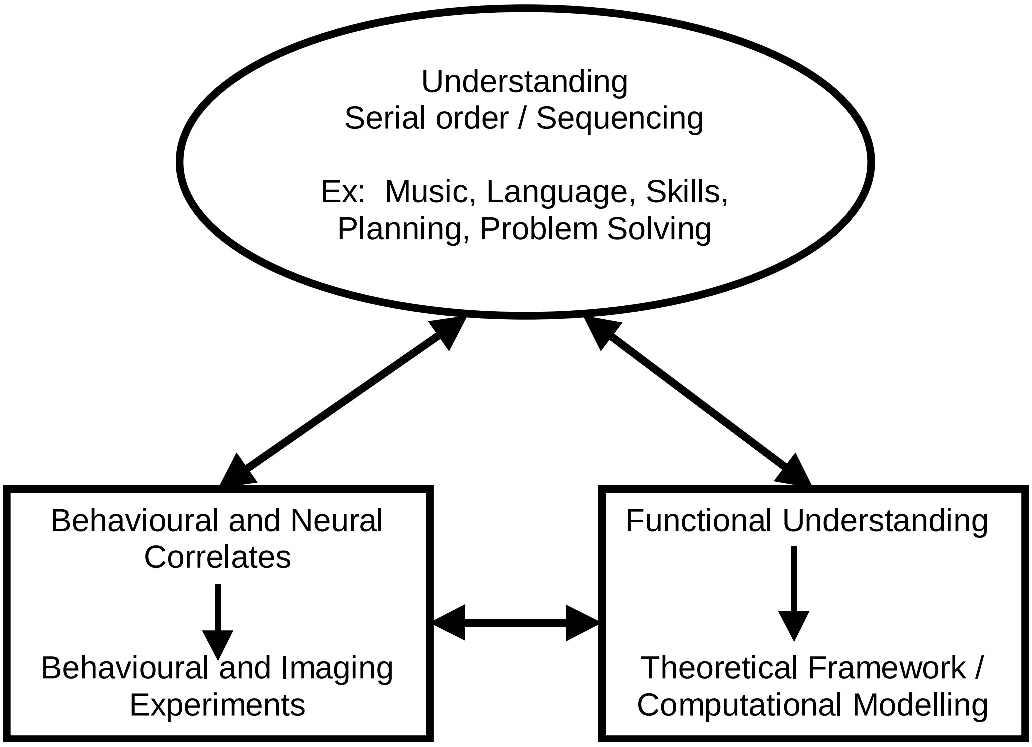


Figure 8: Block Diagram Depicting the Scientific Endeavour. Relationship between experimentation and modelling is emphasized in promoting the understanding of Serial Order**.**

In the previous sections we presented evidence from empirical experiments. Now, we propose a theoretical framework. Only the chaining and learning aspects are considered here and other aspects of serial order described in the previous sections are not emphasized in the current framework. It is hypothesized that sequence learning involves two levels — at the first level lower order sequential dependencies are extracted and then at the second level the entire sequence structure is learned via reinforcement learning. A combination of Markov models and reinforcement learning is suitable to capture the function of the two levels.

Markov models is a nice mathematical framework for capturing first and higher order sequential dependencies among random variables describing the behaviour of a system. The main assumption here is that the past history is redundant in predicting the next state.

First-order Markov Model: The probability that q_t (state at time t) is equal to j is completely predictable by knowing what the state was at time $t-1$ and ignoring the rest of the past history. A formal definition is given below.

$$P(q_t=j \mid q_{t-1}=i, q_{t-2}=k, \ldots) = P(q_t=j \mid q_{t-1}=i)$$

Reinforcement learning has been proposed as a biologically realistic framework for learning sequential decisions in animals and humans (Sutton and Barto, 1998). In this paradigm, the sequential decision problem involves assuming a policy (a mapping from the states to possible actions) and learning a value function over the state space so that the sequence of actions maximizes the expected future reward. The most popular method for learning the value function is the method of Temporal Difference (TD). A formal definition is given below.

Reinforcement Learning:

Value of a state : $V(t) = E\,[r(t+1) + r(t+2) + \ldots]$

Policy & Reward Prediction Improvement by TD: $\delta(t) = r(t) + V(t) - V(t-1)$

We propose to undertake computer modelling (simulations) using a combination of markov models and reinforcement learning in future to investigate if models based on this framework can really learn sequences. Further, we need to see what insights the modelling effort gives in driving the future empirical work.

5.0 Conclusion

An introduction to Serial order, an essential aspect of human behaviour, is given. An exhaustive summary of various aspects of serial order is given in the paper. The issues discussed are the origin, representation schemes, organization, order, timing, learning and perception. A summary of brain areas related to sequencing and our empirical efforts in this direction are given. A theoretical framework combining the mathematical ideas of markov models and reinforcement learning is proposed for understanding chaining and learning aspects in sequencing. It is also emphasized that in any scientific endeavour toward understanding a cognitive phenomenon, an approach that combines empirical approach and theoretical/modelling effort is very much indispensable.

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