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The Nature of the Traces and the Dynamics of Memory

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Abstract: The aim of the present article is to show that current single-system models, clearly located in a dynamic memory perspective and embodied, had brought answers to questions that appeared in the Atkinson and Shiffrin model, that has been the reference for multi-system memory models for 50 years: one concerning the question of recovery in memory and the other the nature of the traces in memory. Our focus will be to show that it is not possible to define storage and recovery processes without taking account of the contents of memory and the dynamics of the emergence of knowledge. Two models will be presented, both defending the idea that it is not possible to distinguish between process and content, as memory does not encode and retrieve contents but reusable processes. In other words, these models suggest that knowledge is in a state of constant reorganization due to a combination of the subject's activity and environmental constraints. That is to say that they consider memory as a dynamic system. Consequently, the traces cannot be dissociated from the mechanisms that gave them birth. It is certainly on this point that the most radical break between these models and anterior models of memory.

Keywords: Memory Traces, Single-system Model, Dynamic Knowledge, Fractal Architecture

1. Introduction

There can be no doubt that Atkinson and Shiffrin's (A & S) model [1], "*Human memory: A proposed system and its control processes*", prompted a surge of interest in human memory and lies at the origin of all the work that has taken place since it was first proposed. To summarize the model, A & S suggested that there is a dichotomy between memory structure and control processes. Moreover, with regard to the structure of memory, a distinction is made between active structures (sensory systems and short-term storage) and a passive structure (long-term storage), with the former having limited capacity and the latter constituting permanent storage. Control processes are the processes used by the subject to remember and are not a permanent feature of memory (rehearsal, coding, transfer, search, decision). Since its publication, several works have validated various aspects of the model, while others have been more critical as is clear from the book published for the 30th anniversary of the A & S model (Hockley [2]).

The A & S memory model presented here, as well as its extension SAM (Raaijmakers & Shiffrin [3, 4]; Gillund & Shiffrin [5]), is essentially a model that accounts for recall. It is therefore understandable that the central process for retrieving information from the set of stored information is the search process. However, memory recovery is not limited to recall. Categorization and recognition are other processes used to recover information. We can therefore ask whether the search process is the most relevant when attempting to account for recovery. Reading their article, it also appears that A & S had doubts about this: "Search processes seem at first glance to offer an easy means· for the analysis of differences between recognition and recall. One could assume, for example, that in recall the search component which attempts to locate information on a given item in LTS is not part of the recognition process; that is, one might assume that in recognition the relevant information in LTS is always found and retrieval depends solely on matching the stored information against the item presented for test" (p. 186).

In this contribution, our focus will be to show that it is not possible to define storage and recovery processes without taking into account the contents of the memory, and more particularly the nature of the traces in long-term memory. A & S also raised this question concerning the search process:

"Consider first the possible forms of search mechanisms and the factors affecting them. ... The factor determining the form of the search is the nature of the trace in long-term store" (p. 181). We argue that the way we consider the nature of the memory trace reflects how we view memory.

In A & S, storage mechanisms are highly dependent on control processes by means of which the subject decides what to store, when to store, how to store and where to store information in LTS. Recovery processes are also highly dependent on control processes and consist of a succession of recursive processes through which information is successively searched for, selected for examination, and recovered until the subject considers that the correct information has been retrieved (the search then terminates and a response is emitted).

Both the distinction between storage mechanisms and recovery mechanisms and the necessity of control processes derive to a large extent from the distinction made between memory systems, sensory registers, STS, and LTS. However, A & S admit that "*our hypotheses about the various memory stores do not require any assumptions regarding the physiological locus of these stores; the system is equally consistent with the view that the stores are separate physiological structures as with the view that the short-term store is simply a temporary activation of information permanently stored in the long-term store." p. 179-180.* Similarly, they recognize that "*although storage and retrieval are separate, we do not wish to imply that these processes are separated in time, one following the other."(p. 183).*

In the complementary models proposed in this paper (Act-In and Athena), a) memory is considered as a single system, b) it is not really possible to consider the storage and recovery mechanisms independently of one another, and perhaps more importantly, c) control processes have a very limited role.

2. A Single System of Memory Containing Traces and the Question of the Independence of the Traces

An alternative to the structural models of memory has emerged as of the 1980s in the form of the *multiple trace models* in which a single memory system stores traces of individual experiences, that is to say the experiences of our interactions with the environment (i.e, episodic traces), in a multi-sensory and distributed way over the entire brain (Brooks [6]; Hintzman [7, 8]; Logan [9]; Whittlesea [10]; Versace et al. [11]). Consequently, traces reflect the processing episode and its different components. In these models, access to knowledge is the result of a coupling between the recovery situation and the set of activated episodic traces depending on their similarities with the characteristics of the recovery episode. This is what Tulving [12, 13] called the *synergistic ecphory process* and what Hintzman modeled in MINERVA2 [7. 8].

However, two main criticisms can be levelled at multiple trace models (see, Versace et al. [11, 14]) The first relates to the independence of the memory traces: the multiple trace models hypothesize that there are memory traces which are specific to each experience and which are therefore independent of one another. The major consequence of trace independence is the inability of these models to account for a primary characteristic of memory, namely the integration of trace contents into a coherent whole. The second criticism relates to the architecture of memory. The multiple trace models propose a general operating principle and this principle can be implemented in various architectures. Neither Hintzman, nor Logan, for instance, nor the composite trace models (Murdock, [15]; Metcalfe [16]) have proposed any such architecture. To answer these criticisms, and to return to the question of the storage and recovery processes discussed by A & S, we will refer in the present paper to a theoretical model, Act-In, proposed by Versace et al. [11].

The Act-In model is based on four main assumptions: a) memory traces reflect all the components of past experiences and, in particular, their sensory properties as captured by our sensory receptors, and actions performed on the objects in the environment. Memory traces are therefore distributed across multiple neuronal systems which code the multiple components of the experiences; b) knowledge is emergent and is the product of the coupling of the present experience with past experiences; c) the brain is a categorization system which develops by accumulating experiences and which, by default, produces categorical knowledge; d) the emergence of specific knowledge (memories or episodic knowledge) requires simple mechanisms which occur during learning and during retrieval (i.e. interactive activation and integration).

The first assumption takes up the main postulate of the multiple trace models but does not deal with the question of the independence of the traces. The multiple trace models hypothesize that the traces are independent in both space (locatable) and time (the content of a trace does not depend on the content of previous traces and has no effect on the content of subsequent traces). Even though the authors, and Hintzman in particular [7], do not claim that traces can be retrieved in isolation (the content of the echo never reflects the content of a single prior trace), it seems difficult to argue in support of independent memory traces.

Versace et al. [11] assume that there is no contradiction between the idea of a memory system which retains episodic traces and that of non-independent traces, which are spatially and temporally distributed. As the same neuronal areas code multiple traces, adding a new trace modifies the old traces. This means that memory traces are non-independent spatially (they share the same neuronal structures), but also temporally, both in a proactive manner (the content of a trace depends on the content of previous traces that are activated), and in a retroactive manner (the content of a trace modifies the content of previous traces). In fact, the traces symbolize the specific states of the cognitive system. These states could be differentiated from one another even if the underlying traces are not independent.

3. Storage and Retrieval Mechanisms

If LTS is defined as a single memory system that stores traces of individual experiences, how can we account for the storage mechanisms described by A & S (transfer, placement, and image production) and for the recovery processes (search, recovery, response generation)? We said before that memory traces are non-independent temporally, because the content of a trace depends on the content of previous traces that are activated, and the content of a trace modifies the content of previously stored traces. We can therefore see that it is not possible to consider storage and recovery separately, because storage is dependent on what is activated and recovery cannot be performed without changing the memory (without storage).

In Act-In, just as in the multiple trace memory models, knowledge is assumed to emerge from the activation, by the present experience, of multiple memory traces of past experiences. Act-In assumes that the nature (e.g., episodic or semantic) of the knowledge that is likely to emerge depends on the dynamics of two mechanisms which operate in parallel, *namely inter-trace activation and intra-trace activation*. Inter-trace activation refers to the spread of activation from the present experience to and between the different traces. For example, seeing a birthday photograph activates all traces in memory corresponding to situations in which we have been confronted with similar visual scenes (i.e., other anniversaries or any other similar type of celebration). However, in our example, seeing a photograph of a birthday should also activate, at the level of each of the traces involved, the other sensorimotor components associated with this type of image, for example sounds (songs, lyrics, music ...), smells (chocolate, candles ...), tastes, actions. In Act-In, this activation between components at the level of each individual trace is called intra-trace activation. When considered more globally, in terms of sensorimotor dimensions and not at the level of individual traces, it is instead called intermodal activation. Therefore, activation propagates both between traces and between trace components. It is triggered by the properties actually present in the present experience (in our example the image of the birthday), but also by the properties re-activated in memory but not present in the current experience (smells, sounds, actions ..., related to birthday-type situations).

The SARKAE (Storing and Retrieving Knowledge and Events) model recently proposed by Nelson and Shiffrin [17], which represents a further development of prior models (SAM, Raaijmakers & Shiffrin [3, 4], 1980; Gillund & Shiffrin [5]; REM, Shiffrin & Steyvers [18]; REM-II model, Mueller & Shiffrin [19]), starting with the A&S model, has similarities with single trace models. Indeed, SARKAE adopts the view that retrieval is cue-dependent: cue memory is compared in parallel with the stored traces and the activation strength and the results of this govern retrieval (p. 361). Moreover, only traces sufficiently similar to the cue (i.e., traces that are sufficiently activated) participate in retrieval. Finally, the knowledge trace corresponding to a presented item is missing or weak, the item is encoded in terms of traces similar to the present item (p. 383).

If Act-In shares these characteristics Versace et al. [11] also postulated that another mechanism, namely *integration*, is necessary to access elaborate and unitary knowledge. Act-In argues that integration is a dynamic mechanism. This means that some activation occurs continuously and in parallel with the computation of similarities, and that while the integration mechanism is running, the system constructs and elaborates different forms of knowledge in a non-linear way.

It is the intermodal activation that is responsible for integration, whether at the level of a specific trace (intra-trace activation) when specific knowledge emerges or at a more global level (inter-trace activation) when categorical knowledge emerges. It is therefore the integration mechanism that permits the creation of particular entities that are more than the simple sum of their components. Before Act-In, Damasio [20] had highlighted the importance of the integration mechanism in accounting for brain functioning in both perception and recall, something which he refers to as the *binding problem* (p. 29).

The question remains of how to account for the emergence of different forms of knowledge (episodic and semantic). According to Act-In, a high level of inter-trace spread of activation at the level of each trace component, coupled with cross-modal activations (intra-trace activation of properties that are therefore not specific to isolated traces), should permit the emergence of categorical knowledge: This knowledge reflects the components which are most frequently found in the activated traces and which are therefore characteristic of classes of objects (or experiences). In contrast, the emergence of specific knowledge should require only a limited inter-trace spread of activation, coupled with intra-trace activations specific to isolated traces.

In A & S, recovery processes (search, recovery, response generation) are described in this way: *The search process is a recursive loop in which locations or images are successively selected for examination. As each image is examined, the recovery process determines how much information will be recovered from the image and placed in STS. The response generation process then examines the recovered information and decides whether to continue the search or terminate and emit a response."p. 183.*

Even though, in SARKAE, the distinction between “event memories” (i.e., episodic memory) and knowledge (i.e., semantic memory) is not a fundamental functional distinction (p. 360) and “*event memories and knowledge interact at all phases of storage, coding, and retrieval*” (p. 356), event memory traces and knowledge traces are nevertheless two distinct entities. Moreover, “*knowledge traces develop by accumulation of information from event traces and these do accumulate counts in given feature value slots"*(p. 378).

To conclude, there are three major differences between the design of the memory model underlying the A & S model and the Act-In model.

In Act-In, it is the same mechanism (i.e., integration) that makes it possible to recover an item of categorical knowledge or specific knowledge which results from the characteristics of the problem. This is why these types of knowledges are considered to emerge rather than being recovered as in A & S model and further developments.

Since the integration mechanism is dynamic and nonlinear, this means that emerging knowledge is not simply the sum of the components that compose it. It is a new entity in its own right and contains more information than the sum of its components (contrary to SARKAE).

Due to the integration mechanism, it is not the components themselves that are preserved. Instead, the ability of the cognitive system to extract knowledge from them that is reinforced with experience and memorized. This implies a non-independence of the traces as is the case in Act-In, in which there is an interaction between intra- and inter-trace activations.

4. Modeling the Dynamic of the Traces

To summarize, the major contribution of Act-In to the multiple trace models was to suggest that knowledge is in a state of constant reorganization due to a combination of the subject's activity and environmental constraints. In other words, Act-In suggests that we should consider memory as a dynamic system, as formulated in the theory of *dynamic systems* (Abraham, F., Abraham, R. & Shaw, [21]).

Recently, Briglia et al. [22]proposed a mathematical formalization of this dynamic in the ATHENA model.

The ATHENA model integrates the synergistic ecphory principle modeled in MINERVA 2, the inter-dependent evolving traces present in Act-In, and the sensorimotor covariances that are to be learned by an enactivist system.

Even though ATHENA is based on the mathematical formalization of MINERVA2, several modifications have been made. Regarding the principal criticism that can be levelled at MINERVA2: the independence of traces, ATHENA accounts for the contextual dynamics of traces and for the global activity of memory, which MINERVA2 does not do. Through the integration process proposed by Act-In, MINERVA2 accounts for inter-trace integration whereas it does not account for inter-component integration, which ATHENA does. Moreover, while MINERVA2 memorizes the information present in the probe, it does not, unlike ATHENA, account for the manner in which the information present in the probe was processed.

However, ATHENA is not only an implementation of Act-In. It also extends the synergetic ecphory process and the integration process. Referring to the enactivist idea that the experience of seeing occurs when the organism masters sensorimotor regularities or sensorimotor contingencies (O'Regan & Noë [23]), ATHENA learns covariances. Indeed, what needs to be memorized is the coupling between the present experience and the trace of past experiences through the sensorimotor system. In other words, what needs to be memorized are the covariances between the present sensorimotor information processing and past sensorimotor information processing. These covariances are sufficient to account for cognitive information (Hutto & Myin [24]) because if two processes are covariant, they are probably linked. Moreover, based on the intensity of the covariance, we can infer the probable link between present and past information processing. This can therefore account for the emergence of memory.

In addition to the concept of covariance, ATHENA also takes account of one of the major characteristics of Act-In, which is referred to as the scale invariance of the integration process (i.e., local and global, Versace and al. [11]). Thus, each trace must evolve as does memory in its entirety. That is to say that each trace, in the same way as memory in its entirety, must remember the covariances between each situation encountered and their local processing. Consequently, memory learns and processes the memory processes themselves. To do this, ATHENA uses a fractal architecture: the global memory model consists of several memory models in the same way as the global model. Consequently, in ATHENA, it is the old traces that make it possible to interpret the new traces and this interpretation is a part of memory. Moreover, the old traces are modified based on new situations and the old ones learn how they have made it possible to learn the new ones. Finally, the fractal matching between the ongoing situation and the previously learned situations allows ATHENA to account for the historicity of the composition of the traces as well as for memory in its globality. In other words, ATHENA is able to account for the dynamic of memory, that is to say its constructive and reconstructive character, which has been known since Bartlett [25]. Indeed, in ATHENA, "*each trace learns how the information that led to its creation has been processed – it constructs itself – as well as how it helps to process incoming information – it reconstructs itself. In the same manner, the memory (i.e. the totality of the traces) learns how the encountered pieces of information have been processed – it constructs itself – as well as how it continues to process the information – it reconstructs itself continually*" (p. 102).

To summarize, there are three main features that distinguish ATHENA from the models from A & S: a) memory traces are not independent; b) only covariances stand for information; c) it is not the content of the retrieval that is memorized but the memory processes themselves, which can then be reused as the situation demands; c) ATHENA is a dynamical model. Indeed, each trace of the ATHENA model is directly linked to the others. Since traces are in non-linear dynamic interaction and compete to provoke the emergence of the optimal contextual interpretation of the whole memory (p. 950). As this dynamic seems secondary in SARKAE (p. 379): "*The SARKAE simulation for event recognition did not utilize dynamic assumptions (...) a dynamical model would have added much complexity for little purpose*».

5. The Question of Event Memory

As Nelson and Shiffrin write [17] p. 385, "*With few* *exceptions, the field has not explored the issue* (see Zacks & Tversky [26])". However, it is generally accepted that an event exists in memory and contains different types of information: information relating to the task and the associated stimuli; information relating to the situation; information relating to the functioning of the cognitive system itself.

Among the information related to the functioning of the cognitive system, ATHENA is able to account for an *inferential process* that occurs during recognition. This is what is referred to as the *heuristic of fluency* (Jacoby, Kelley & Dywan [27]). While the familiarity felt is an important cue in the judgment of recognition, it is not necessarily associated with the previous presentation of the stimulus. As these authors indicate, the familiarity of a stimulus may be the product of an *attribution process* associated with the subjective and unconscious perception of cognitive functioning as a result of stimulus processing. In other words, familiarity is the product of an unconscious inference about the source of the fluency felt in the execution of a task (Whittlesea, Jacoby & Girard [28]; Whittlesea [29]).

This inferential process is not present in MINERVA and Act-In. In these single-system models, it is the possibility of coupling the trace of the present experience to the traces of past experiences that gives emerging knowledge the characteristics of knowledge (i.e. the memory experience). But according to the SCAPE model (Selective Construction and Preservation of Experience, Leboe-McGowan & Whittlesea [30]; Whittlesea [31, 32]; Whittlesea & LeBoe [33, 34]; Whittlesea & Williams, [35-38]), the recovery of knowledge involves two stages: a) the construction of a mental state that is the product of the pairing between the components of present cues and the components of past experiences, and (b) the occurrence of a subjective feeling of familiarity, which is the product of evaluation and inference. Here, the evaluation does not refer to a judgment on the stimulus, but to a judgment on access to the constructed mental state (i.e. easy vs. difficult access). The inference is based on the feeling that results from access to the constructed mental state. That is, people try to attribute to an objective source (i.e., stimulus) the subjective feeling related to access to the mental state (Whittlesea & Williams [35]). Since the person is not aware that the mental state is a construct, they use a basic attribution process: if I feel that access to this mental state is easy, it means that I have already been in contact with the stimulus. Indeed, people have already experienced that something known is easier to process than something unknown. In other words, they commit an attribution error that leads them to produce a judgment of recognition (Whittlesea [39]).

To summarize, emerging knowledge is not only the reflection of this coupling but is also the consequence of the way in which access to this memory experience has been subjectively evaluated. More specifically, the object of the evaluation process is the process of constructing the mental event itself (i.e., the coupling between present experience and past experience). In other words, it is the subjective fluency associated with the construction process that serves as an indicator of the realization of this construction. Therefore, it is through an inference mechanism that the constructed mental event may become a memory.

As the memory of a memory activity is defined by the fluence of the current processing, we must, if we are to model it, quantify the fluence with which all memory traces are confronted with the sensorimotor situation. In MINERVA2, the intensity (sum of activations) corresponding to an objective quantification cannot account for this. To do this, Athena models fluence based on an inference process (Schwartz, Benjamin & Bjork [40]; Benjamin, Bjork & Hirshman [41]). Indeed, a memory model based on an inference process is able to extrapolate a memory from very little information (Tenenbaum et al. [42]), thus reducing memory noise (Bitzer et al. [43]; Osth & Dennis, 44). This allows Athena to account for the subjective feeling of recognition, unlike MINERVA2 (Benjamin, Bjork & Hirshman [41]).

It should be noted that Nelson and Shiffrin [17] p. 379, consider that this process should be implemented in SARKAE (in the way suggested by Cox and Shiffrin [45]).

6. Conclusion

We introduced this article marking fifty years of the A & S model with two questions formulated by the authors, one concerning the question of recovery in memory and the other the nature of traces in memory. By referring to the non-structural models of memory (i.e., single-system models), we wanted to show that we could account for the recovery of knowledge other than through a search-and-recovery mechanism as in the A & S model. However, a recent contribution by one of the authors of the A & S model, namely Shiffrin (i.e., Nelson & Shiffrin [17]), in the form of the SARKAE model, adopts the view that retrieval is cue-dependent. However, while in SARKAE, retrieval is the consequence of recovery mechanism, we show, in the Act-In model, that it is possible to account for recovery in memory through the emergence process.

Regarding the nature of traces in memory, this question is still relevant, even in the single-system models. For a model like MINERVA2, the traces are contents (i.e., sensory and motor components), whereas for Act-In, and to an even greater extent for Athena, the traces cannot be dissociated from the mechanisms that gave them birth. It is certainly on this point that the most radical break between the A & S model and these later models is to be found. Indeed, structural models such as A & S or single-system models like MINERVA2 distinguish between process and content, which is not the case for Act-In and Athena. Thus, these differences regarding the nature of the traces lead to radically different conceptions of memory. Memory does not remember recoverable contents but reusable processes. More specifically, memory remembers the processing used in encountered situations.

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Biography

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Versace Remy, Professor, University Lyon 2, EMC Laboratory, Denis Brouillet and Remy Versace conduct research on human memory in an enactivist approach to human cognition