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The Theory of Neural Cognition Applied to Robotics

Invited Review Article

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Abstract

The Theory of neural Cognition (TnC) states that the brain does not process information, it only represents information (i.e., it is 'only' a memory). The TnC explains how a memory can become an actor pursuing various goals, and proposes explanations concerning the implementation of a large variety of cognitive abilities, such as attention, memory, language, planning, intelligence, emotions, motivation, pleasure, consciousness and personality. The explanatory power of this new framework extends further though, to tackle special psychological states such as hypnosis, the placebo effect and sleep, and brain diseases such as autism, Alzheimer's disease and schizophrenia. The most interesting findings concern robotics: because the TnC considers the cortical column to be the key cognitive unit (instead of the neuron), it reduces the requirements for a brain implementation to only 160,000 units (instead of 86 billion). A robot exhibiting human-like cognitive abilities is therefore within our reach.

Keywords Self-organizing Maps, Cognitive Abilities, Consciousness, Artificial Intelligence, Robot-sitting

1. Introduction

As long as we consider neurons to be important elements in cognition, we can regard the cortex as the most important structure, since it amounts for about 82% of the human brain mass, even if it holds only 19% of all neurons [1]. The human species differs from other primates; with smaller bodies but larger brains than great apes, it boasts a brain five to seven times 'too large' for its body size [2]. It is therefore logical to begin this paper by investigating cortical organization, in order to unravel the secrets of cognition (Section 2). Section 3 goes on to explain how a hierarchical memory is able to act, through the synergy of pairs of cortical maps. Complex behaviours are easily generated, with the additional help of the time and space indexes provided by the hippocampus. The various types of memory are explained relative to their use of these indexes. Personality traits are defined by near-permanent cortical column activations.

In Section 4, we present the dynamics of this hierarchy of cortical maps and answer questions like "how many data are required for the self-organization of a map?". The cortical organization required to learn orthographic reading skills is modelled by six successive cortical levels, and illustrates the implication of additional learning strategies, such as the novel 'palimpsest learning' strategy. Section 5 is devoted to endogenous and exogenous attention orientation, a perfect occasion to discuss several of the side effects of a hierarchy of self-organizing maps, such as consciousness and predictions. Section 6 describes the initialization of behaviours that may be related to motivation, and its dynamics that define intelligence and cognitive planning. This section also addresses the role of the amygdala and how it induces emotions. In Section 7, special psychological states, such as hypnosis, sleep and the placebo effect, are explained using the TnC framework. Section 8 briefly analyses three major diseases (autism, Alzheimer's disease and schizophrenia), in order to demonstrate the explanatory power of the TnC. Its predictive power is then tested (Section 9) through the specification requirements for a conscious robot based on the TnC framework, demonstrating that the bottleneck is not in computing power anymore, but in the duration of the learning process (in terms of years).

2. A hierarchy of self-organizing maps

The human cortex [3] is about 0.6 m x 0.6 m in size, and between 2 to 3 millimetres thick. The number of cortical neurons is 16 billion (19% of 86 billion). These neurons are organized in mini-columns of about 110 neurons, which extend from one side of the cortex to the other (2-3 mm). About a thousand of these mini-columns form a macro-column, a functional unit evidenced in 1959 by Nobel laureates Hubel and Wiesel [4].

In the context of the TnC [5], we consider the cortex architecture to be homogeneous across its entire structure. Each neuron belongs to a given (macro-) column, and the cortex is made up of only 160,000 cortical columns. These cortical columns are grouped into multiple maps of several hundred units. We know the functionality of many of these maps, in particular the maps that constitute the primary cortex, whose name ('primary') comes from the fact that each of its maps encodes data belonging to only one modality (audition, smell, proprioception, vision, etc.). The maps that constitute the secondary cortex receive data from the primary cortical maps, and fuse data from multiple modalities or dimensions. What is left has been named the 'associative cortex' (i.e., where 'associations' are made) and encompasses about 70% of the cortical columns (57% of the total brain mass). Little is known about the associative cortex, except that a sensory cortex can be distinguished from a motor cortex, as evidenced by Penfield and his famous sensory and motor 'homunculus' 75 years ago [6].

Cortical columns do not bear the physiological limits of neurons [7]. While a given neuron tires quickly (in a few tenths of a second), a column with 110,000 neurons does not. While a neuron can only exhibit a binary state (excited or not), a 110,000-neuron column may display graded activation. From now on, we will assume that the cortical column is the functional unit of cognition.

About 40 years ago, Kohonen [8] proposed a modelization of the cortical map, which became famous under the name of its inventor: the 'Kohonen map' or 'Self-Organizing Map' (SOM). By modelling the fact that neighbouring columns inhibit each other, Kohonen showed that map columns compete: the first to achieve activation wins and silences the others. The winning column adjusts its synaptic efficiencies, as do its closest neighbours. These adjustments follow Hebb's law [9], a 70-year-old neural learning rule for which there is increasingly more evidence [10-11]. The result of these synaptic weight modifications is to guarantee that, in the future, the winner would win again if the same conditions (data) were applied (i.e., the same inputs into the map). If the inputs are not identical, but similar, then either the winner wins again, or one of its closest neighbours wins. Thanks to this behaviour, the SOM is today one of the most efficient tools for multidimensional data projection onto a 2-D surface, since its projection respects both the topology of the input space (multidimensional neighbour data are neighbours on the 2-D surface) and data distribution (the most frequent data are better represented on the surface).

Since the SOM models a small part of the cortex, the whole cortex could be said to construct multiple 'optimal' 2-D representations of the real world. Indeed, already 80 such maps have been evidenced in the human brain [12]. Each map is devoted to a particular aspect of the world situation, taking into account their neighbourhood properties (sounds with sounds, images with images, etc.). What is not a neighbour at one level of abstraction may become a neighbour at a higher level of abstraction. This possibility is afforded by the hierarchical organization of the cortical maps (Figure 1). The idea that the cortex is a hierarchy of cortical maps is by no means new. Many researchers have already stated this fact [13-14], but none have been able to explain how this hierarchy of memories is able to act, behave, pursue goals, and show intelligence, motivation and consciousness, which is the aim of the TnC.

The hierarchy is an anatomical and functional one: the primary cortical maps (layer 1) send their outputs to the secondary cortical maps (layer 2), which send their output to the cortical maps of layer 3, etc. The level of abstraction of a particular map is given by the number of maps that separate it from the primary cortical inputs.

Figure 1 could be misleading in several aspects. The true number of layers amounts to more than 10, as evidenced by the fact that any cognitive task answer requires more than 130 ms, while the processing undertaken by any one map (i.e., competition, winning and transmission) is completed in less than 10 ms. We already know about 80 maps [12]; the TnC proposes that their total number approximates a few hundred (e.g., 160 maps). Lastly, there are no cortical maps that could really be labelled 'objects' or 'words'; however, 'objects that can be seized', 'animals', 'abstract objects', 'orthographic words', etc., are all legitimate labels.

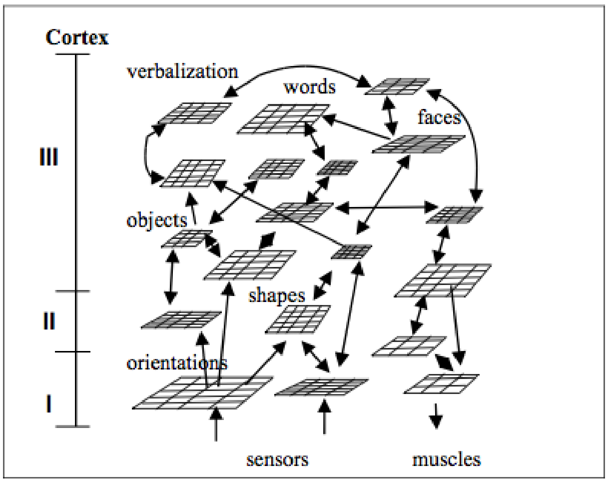

Figure 1. A hierarchy of cortical maps accounting for the primary (I), secondary (II) and associative (III) cortices. Connections are made in both direction (forward and backward).

3. A memory that acts

In a paper published in 2006 [15], we explained how a synergy between two cortical maps can generate a robot's behaviour instantaneously, without the need for any prior knowledge of the desired task, and how the robot's performance improves through the mere repetition of the behaviour.

3.1 Elementary behaviours

The first of these maps is the situation map. The data used for its learning are the successive situations measured by the robot's sensors. The other map is the situation variation and associated action map. Its learning data are the successive actions achieved by the robot and the respective variations of situations that these actions generate. In order to instantaneously synthesize a behaviour, one has to set a goal for the robot. This goal is a desired situation, i.e., a location on the situation's map (or sensory map). The experienced situation, at time *t*, is another location on the map. Due to the continuity representation of the SOM, there exists a trajectory on the map that goes from the current location to the desired one. This trajectory is almost continuous; therefore, in our context, any two neighbour columns belonging to this trajectory will code for not so different situations (almost similar). Thus, an action will exist that is able to modify the experienced situation, in order to change it to the one coded by the neighbouring column (the intermediate situation in Figure 2). Having completed the action, the current situation (at time *t+1*) will now be the previous intermediate situation. From there, a new intermediate situation is selected (a neighbour of the current one, but closer to the goal situation); the variation between the current and new intermediate situations is then computed and the second map provides the action needed to achieve the change in situation. The process is repeated automatically until the current situation finally becomes the goal situation.

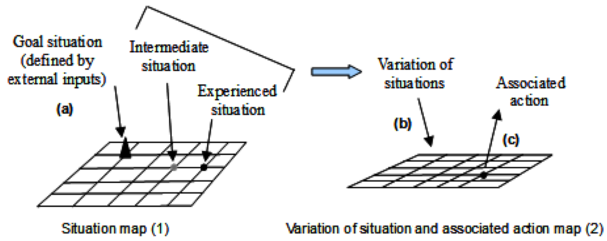

Figure 2. Two cortical maps cooperate in order to generate a sequence of actions (i.e., an elementary behaviour) in response to experienced situations. Each intersection represents a cortical column. The topology of the input situation space is preserved by the first cortical map (Situation map (1)). The situation adjacent to the experienced situation and closer to the goal situation (a) is the intermediate situation (which will have to be reached) in the process of achieving this 'goal'. The difference between the experienced and intermediate situations (b) serves as the input to the second map (Variation of situations and associated action map (2)). Probing an associative memory (map 2) with information will automatically complete the information. In this case, it furnishes the action (c) associated with this variation between situations (i.e., the action that needs to be accomplished in order to achieve a change from the experienced situation to the intermediate one).

It is important to mention that activating any cortical column different to the cortical columns involved in coding for the currently experienced situation (i.e., the setting of a goal situation) automatically activates the connected maps. When one of these maps belongs to the sensorimotor cortex, this results in actions.

3.2 Complex behaviours

More complex behaviours can be achieved by involving more than a single pair of sensory and sensorimotor maps. For example, in order for a mobile robot to fetch a bottle of water and bring it back to the office (a complex behaviour), it has to go to the kitchen (a first elementary behaviour – EB 1), find a bottle (EB 2), grab it (EB 3) and bring it back (EB 4, which uses the same cortical maps as EB1, but with a different goal: the office) (Figure 3).

EB 1: One map codes for the x and y locations of the various rooms, and the second map memorizes the variations between positions associated with actuator commands. The experienced situation is the office. The goal situation is the kitchen. The successive intermediate situations include the office-corridor door, the corridor, and the corridor-kitchen door. The actions involve moving from one x-y position to another, which implies that the office-corridor door is identified by its x-y coordinates, as is the corridor-kitchen door, etc. This (elementary) behaviour automatically stops as soon as the current situation and the goal situation are identical (i.e., coded by the same cortical column of the situation map).

EB 2: Once in the kitchen, a second pair of SOMs is activated; the first of these maps encodes the objects and their respective locations in relation to the body (ego-centred). The robot's goal is the visual form of a bottle. The second SOM turns the head around. This behaviour stops as soon as the bottle is located. The goal (shape of a bottle of water) has been provided in the initial request ("bring back a bottle of water"). The goal of the next behaviour (EB 3) is provided by EB 2 (i.e., to reach the ego-centred position of the bottle).

EB 3: A third pair of SOMs takes care of the grabbing task: one map encodes the ego-centred position of the robot gripper, and the second map elicits the actions needed for it to reach the desired position. As soon as the bottle has been grasped, EB 3 is terminated, and the next goal is provided by the initial request ("bring back to the office").

EB 4: This behaviour is implemented by the same cortical maps as EB 1, but the situation-goal is different: it now codes for the office.

The switching from one pair of SOMs to the next is automatic: as soon as the experienced situation matches the desired one, the sensorimotor map is deactivated and the next pair of SOMs is activated instead. Either the new goal situation is already known (i.e., given in the initial settings, for example 'bottle'), or it is provided by the pair that has just achieved its goal; for example, the ego-centred coordinates of the bottle (the goal situation for EB 3) are provided by the EB 2 situation map.

Twenty-five years ago, when he affirmed the 'unity of remembered experience' in spite of the fragmentation of memory over multiple maps (with each map devoted to a particular dimension), Gallistel stated that the various maps could be coordinated thanks to two very special indexes: space and time coordinates [16]. Indeed, any event or situation – whatever the sensory modalities – also includes a location and a timestamp. Since maps represent experienced situations (each one associated with a given pair of time and space coordinates), then the activation of one map will in turn activate other maps as appropriate, using these space and time coordinates. Interestingly, in the brain, space and time coordinates are encoded by the hippocampus, a structure more or less equidistant to any given portion of the cortex, and extensively connected to it.

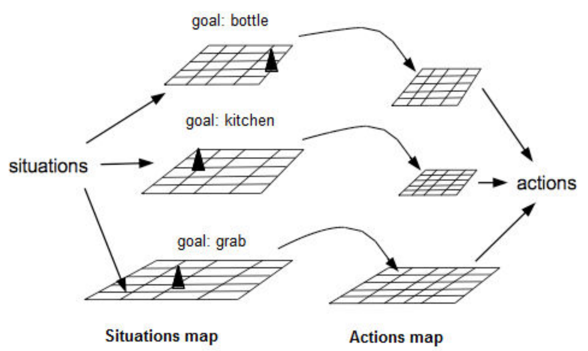

Figure 3. A complex behaviour is the result of several 'elementary' behaviours (go to the kitchen, find the bottle, grab it)

3.3 Personality

A personality trait refers to the enduring personal characteristics that are revealed in a particular pattern of behaviours in a variety of situations. Since behaviours are generated by cortical column activations (situation-goals), near-permanent situation-goals intervene almost permanently in our lives. This set of near-permanent cortical column activations defines our behaviours: our personality traits.

3.4 Episodic, semantic and implicit memories

Cognitive science partitions (human) memory into several separate processes (declarative, implicit, episodic and semantic memories), while the TnC sees it as a continuum. Episodic and semantic memories belong to the category of declarative memory, which requires conscious recall, and are opposed to implicit memory (no conscious recall). Episodic memory refers to information specific to a particular context, and includes its time and place coordinates, while semantic memory allows for the encoding of abstract knowledge about the world (i.e., information independent of its context). In fact, any piece of information when encountered for the first time is associated with a date and a location, and belongs to episodic memory (also called 'autobiographic memory'). If this information is encountered again in other locations, then the locations become harder to memorize, along with the timestamps. If these time and space indexes do not provide additional information, they are discarded and the piece of information now belongs to the semantic memory. In this way, semantic memory is made up of events whose time and space indexes are irrelevant to the information. If this information continues to be repeated again and again, its relative frequency will increase, and it will therefore come to be represented on the lower levels of the SOM hierarchy, ensuring shorter reaction times. With no access, or a reduced access, to the high-level maps that implement conscious recall (see Section 5.1), no verbalization will be associated with these stored events. These events form the implicit memory, which hosts 'automatic' reactions (reflexes).

3.5 Phonological shape of words

Psychomechanics, a linguistic theory formulated by Guillaume [17], does not agree with the widespread notion expressed in the phrase "*l'arbitraire du signe*", which states that the phonological shape of words is arbitrary. In psychomechanics, a word results from a construction by a speaker with an intention. The meaning of the word influences its phonological shape. The TnC hypothesizes that the various elements associated with the meaning of a word activate pre-existing cortical sensorimotor schemes, thus determining the word's phonological shape. The only difference between the TnC and psychomechanics is that the TnC does not limit targeting to the vocal organs (but includes all other motor organs, such as legs, hands, etc.).

4. Learning within a hierarchy of SOMs

Neuroplasticity results from neurons changing their connection patterns in order to maintain a certain level of activation – neither too much, nor too little. At the SOM level, this behaviour translates into weight adjustments in order to account for data distribution. Since real data are not uniformly distributed, an SOM will only encode a certain percentage of the data that reach it. Following the empirical observation that many natural phenomena exhibit a Pareto distribution (a power law distribution), we hypothesize that 80% of the data account for only 20% of the variations. An SOM will favour the representation of this 'static' 80% of data (those displaying less intrinsic variation: only 20% of the total variation), and will have trouble with the other 20% of data (since it accounts for 80% of the variation). An SOM will exhibit strong and localized activity based on any data belonging to these 80%, and diffuse activity based on other data. Anything 'new' (i.e., belonging to the 20%) will not be recognized (i.e., there will be no specific cortical column activity), and it will therefore continue on its way towards other (higher-level) maps.

Following this hypothesis, a map located one level above (level 2) will only receive 20% of the (100%) data received by the first level maps. A map at level 3 will only receive 4% (20% of 20%) of the data; at level 4, only 0.8% of the data will arrive. The percentage of data reaching level l is therefore given by $(0.2)^l$ (see Table 1). This means that the number of data (i.e., learning samples) quickly becomes very limited, while the process of map self-organization takes longer. It follows that the training of any cognitive ability requires a huge amount of time, or a dedicated learning base that promotes the associations needing to be represented.

Level l	1	2	3	4	10	12
%	100	20	4	0.8	$5\ 10^{-5}$	$4\ 10^{-7}$

Table 1. Percentage of input events reaching any given map at level *l*. The self-organization of any 'high' level of abstraction therefore requires either a very long duration or a dedicated learning base.

4.1 How many data are required to organize a given SOM?

The answer to this question requires firstly establishing the size of the SOM. Using the assumptions already made in this paper (160,000 cortical columns and 160 maps), we get a number of 1,000 cortical units per SOM. If we assume the simplest case of coding, i.e., a one cortical unit/one data, then at least 1,000 learning data are required. Let us remember that one-shot learning seldom occurs. Usually, hundreds of repetitions are required, which puts the required number of samples (for an SOM) close to one million (1,000 x 1,000 = 10^6). If no biases are used, then, in order to organize a level-10 SOM, an agent must experience more than a trillion events (10^6 x 100 / 5 10^{-5} = 2 10^{12}). Assuming that the agent is able to sample the environment at about 25 Hz (since, at this rate, vision is experienced as continuous while additional frames do not add further information), to experience a trillion (i.e., a million million) events, one would need about 31,689 years. We can therefore conclude that high-level cortical maps are either much smaller than hypothesized, or the distribution of the learning samples are biased in favour of their organization.

4.2 Orthographic reading organization

Reading is a complex cognitive ability of tremendous importance. Its neural organization has been modelled by Dehaene (in 2005 [18]) and others [19-20]. The model (Figure 4) involves six cortical maps, starting with the oriented edges of the primary visual cortex and moving up to letters, bigrams (i.e., pairs of letters [21]) and words. Reading is acquired at age five, and the reader's expertise depends on the regularity of the language. Highly consistent languages, such as Spanish, allow their users to read fluently in a matter of months. On the contrary, with its numerous exceptions in pronunciation, English requires two additional years when compared to Spanish.

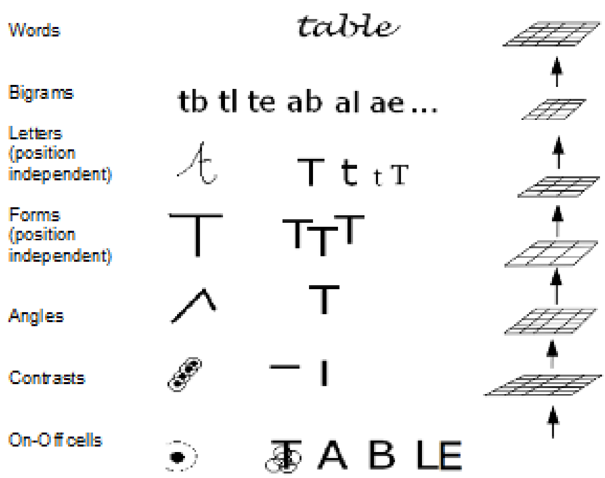

Figure 4. The cortical organization of reading: a hierarchy of six SOMs

The timing of the various maps' (self-)organization follows their abstraction level. For example, it is impossible to organize the bigram map before the letter map. In order to achieve an expert level in reading, French pupils spend five years practising, for dozens of hours per week, which amounts to an impressive 4,000 hours. An expert reader is assumed to have mastered about 2,000 words, and is able to generalize to 5,000 words. This orthographic word representation map size is therefore in line with our hypothesis concerning average SOM size (between a few hundred and several thousand units).

Despite this lengthy duration, the organization of the SOM does not rely uniquely on self-organization, as evidenced by the major setback in literacy teaching associated with the 'whole language' paradigm (in the late 1980s to 1990s). This paradigm differed from the historical phonics method in that there was no explicit training in the association between the letters (graphemes) and the letter sounds (phonemes). To teach such letter-sound associations, the teacher usually provides many samples of letters and their associated sounds, and corrects the pupil until they are able to master approximately eight new associations per week. These training samples bias the event distribution, and represent a kind of supervised training; as long as the association has not yet been mastered, the pupil has to correct his/her answer. The organization of level 4 (letters) within the hierarchical cortical structure of reading is thus supervised, allowing for an easy organization of the upper level of pairs of letters (bigrams). However, with the 'whole language' paradigm, level 4 remained unsupervised, meaning it would take longer to organize and the organization risked being less coherent with upper level requirements (Figure 5).

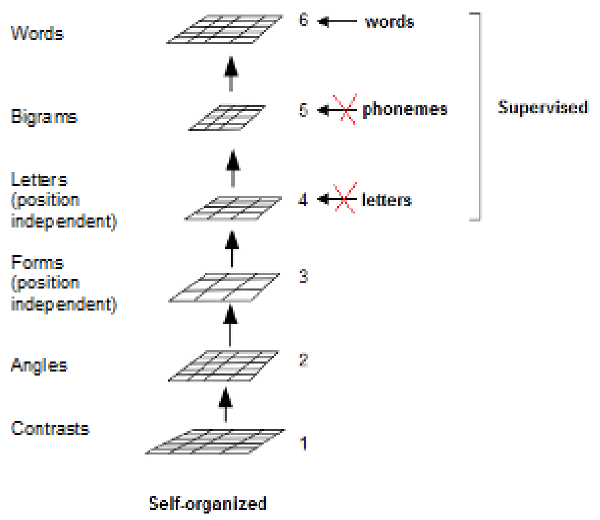

Figure 5. Additional information helps the organization of levels 4 and 5 when using a phonics method, but not in a 'whole language' method (which is today banned for lack of efficiency as a method for learning to read).

The self-organization of high-abstraction-level maps requires a huge number of learning samples, thus necessitating additional teaching procedures. An efficient method consists in explicitly learning intermediate representations useful for the correct organization of high-level representations. At the level of the human teacher, such a method looks like supervised training. At the level of the neural networks, such a method is not supervised, since the teacher cannot provide the desired neural coding output, only a reinforcement signal able to inform the pupil on the efficiency of his/her production (“good” or “not good”). At the synaptic level, where only Hebb's law exists, one must take into account the timing of the synaptic modification to understand why, in order to learn, it is necessary to repeat trials until success is achieved.

4.3 Palimpsest learning

The word 'palimpsest' means “scraped clean and used again”. We apply it to a new learning paradigm which explains how and why neural networks autonomously generate attractors around equilibrium states, with no need for a reference (and therefore no measured error). 'Palimpsest learning' explicitly refers to the duration required by the synapse to change when it 'memorizes' the co-activation of the pre- and post-synaptic neurons. Such modification does not take place instantaneously, but requires (at least) a few seconds to complete. In many situations, before the end of this delay, that particular synapse is solicited again. Two cases are possible here: either the pre- and post-synaptic neurons are again co-activated, or only one of the two neurons is activated (no co-activation). In the latter case, Hebb's law dictates a decrease in synaptic strength, not as drastic as the increase would have been, but nevertheless stopping the initial modification short (and preventing it from ever being completed). The only complete synaptic modifications are those that are not shortly followed by any pre- or post-synaptic neuron activation. In particular, this is the case when equilibrium is reached, i.e., when the frequency of changes is particularly low. In this case, the last 'action' of the neurons is well recorded, and will be easy to replay the next time the situation is similar. By allowing complete synaptic modification only for those associations that are not immediately followed by other actions, this learning paradigm favours the emergence of equilibriums. When applied to biology, these equilibriums may be referred to as 'homeostasis'. The implementation of palimpsest learning requires time to be taken into account. In a simulation, an event-driven simulator could be used.

Looking back at the reading model in Figure 5, palimpsest learning can explain how well-timed additional information (supervision) helps to organize the various cortical maps.

5. Endogenous and exogenous attention orientation

Attention is the cognitive process of selectively concentrating on one aspect of the environment while ignoring others. It remains a major area of investigation within education, psychology and cognitive neuroscience. Therefore, it is of the utmost importance to show how a hierarchy of SOMs can exhibit attention. In order to make this demonstration, the concept of consciousness needs to be introduced, since one has to be conscious of a shift in interest, either through internally generated processes (endogenous) or external stimuli (exogenous), in order to ascertain attentional processes.

5.1 Consciousness

Some of the maps of high-level abstraction represent elements associated with language (orthographic word representations, phonetic word representations, objects that one can grab, animals, verbs, etc.). These maps have been trained as a result of socialization (feral children do not master language, and will never do so if found after the age of seven). This 'training' is mostly provided by the parents, who – sitting close to the child (baby-sitting) – frequently comment on events: “the sky is blue”, “are you thirsty?", "you are tired", etc. There is a timed co-activation of the parents' comments with the experienced situations, which reinforces associations between 'words' and 'events'. After an extended training period, the child will begin to reproduce this behaviour automatically and to 'comment on' the events themselves. In fact, it is only after such a process of commenting, i.e., activating the maps associated with language, that a person can know what he/she is thinking or doing. We consider the behaviour of an agent devoid of language as 'automatic', animal, or without consciousness. The philosophical position that considers consciousness to be just an automatic verbalization of the experienced situation is called 'eliminative materialism', as championed by Churchland [22].

5.2 Backward connections

The hierarchy described in Section 4 only features forward connections between SOMs. From a biological point of view, this is inaccurate since there are as many 'backward' connections as there are 'forward' ones. The reason why the backward connections are usually dismissed, or forgotten, is that their usefulness is not well understood. If neurons A and B both fire within the same time-window, then Hebb's law states that the connection between A and B (A-B) is reinforced, as is the connection between B and A (B-A). If A triggers the activation of B, we can easily see the logic of A-B connection reinforcement, but to reinforce the B-A connection seems acausal.

What is the effect of this 'acausal' reinforcement? It guarantees that the whole SOM network will function as a large associative memory. Changes on lower-level SOMs activate language-level representations, while changes in language SOMs activate lower-level representations. Lower and higher activities are coherent which explains why when you read the words 'pink elephant', this pink elephant immediately takes on a life of its own: you start to see it, smell it, hear it, etc. These perceptions are automatically generated as soon as the words are read, and will also allow for a faster recognition of the situation if you ever do encounter a pink elephant. Since your brain now focuses on this animal, your recognition performance (reaction time) improves, evidencing your so-called 'endogenous attention'.

Endogenous attention is only the pre-activation of the SOM hierarchy, due to language-triggered activities. This pre-activation is automatic, on account of the causal and acausal synaptic modifications. The term 'acausal' should now be dropped since this apparent 'acausality' has been justified.

5.3 Activation trajectory on the SOM

Exogenous attention depends on a different mechanism. Section 2 emphasized that similar inputs are coded either by the same or by neighbouring cortical columns. This guarantees that large areas of the SOM do a continuous temporospatial transform: the successive experienced situations establish an activation trajectory on the map (Figure 6). This is possible because the real world is continuous (at least, at certain levels of abstraction it is).

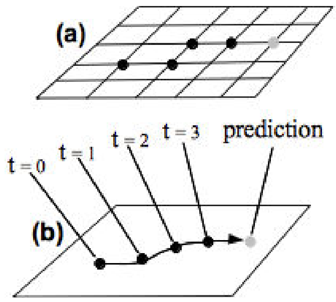

Figure 6. Predicted evolution of the experienced situation. (a) and (b) depict the same map, with and without the neighbourhood drawing.

The fact that, on certain maps, the succession of events forms a continuous trajectory implies that predictions are possible. The next event is going to be either identical to the experienced one, or one that is coded by a close neighbour. Among the various neighbours, the one that maintains the continuity of the current trajectory is the logical choice (Figure 6). This prediction is automatic, in the sense that neighbour columns are inhibited by the winning column, which means that their activation will not be possible (under normal conditions). Higher-level maps will receive no input relative to this event, if such an event does occur. If something unpredictable happens, then it is by definition represented by columns that are not neighbours, and therefore not inhibited. The activation initiated by this unpredictable event will proceed to the highest maps – the language maps. This event will therefore be consciously experienced (because it will be automatically verbalized). Exogenous attention is a by-product of the continuous temporospatial transformation achieved by the cortex, and the SOMs act as novelty filters (filtering out everything that conforms to their continuous representations).

6. Motivation and emotions

Motivation is an inner drive to behave or act in a certain manner. In Section 3, the activation of a goal-situation (i.e., a cortical column on a sensory map) automatically generates a particular behaviour. The question is this: 'who' initially specifies the goal-situations? The answer requires the presentation, in further detail, of the dynamics of activation within a hierarchy of SOMs.

6.1 Dynamics

Each of the several hundred maps exhibits graded column activations. Some of these activations may appear constant, in the sense that they will remain still for a long duration (seconds), while others will flash (ms). The patterns of activations are not random, since the connections among the neurons obey Hebb's law. The patterns represent the events at the various levels of abstraction, with 'constant' activations corresponding to the continuous components of the events, and transient activations representing the various intermediate features of the events. A bad, but instructive, analogy would be that transient activations represent 'calculus', and continuous activations, the 'result'.

A situation is a collection of events, each belonging to a specific dimension (such as the five senses). These co-experienced events are recombined by the hierarchy of SOMs, in order to extract their correlations. The 'constant' activations reflect the highest associations discovered by the system.

Planning (the cognitive ability to reach a goal by selecting a sequence of thoughts and actions) is automatically achieved by dynamic relaxation: set the goal (i.e., activate a particular cortical column of the situation map – the situation-goal), and then allow the system to relax. As time passes, various locations on the SOMs will be activated, which will in turn activate others, etc., until the initial situation-goal is reached and wiped off. The sequence that leads to this is the sequence of actions to undertake in order to achieve the goal.

6.2 Intelligence

Intelligence is a much sought-after component but, following our description, it does not exist *per se*. Each time a new association is established between items A and B, it will involve the *de facto* activation of a column on a higher-level map than those maps representing A and B. If this association belongs to an activation pattern that includes language maps, then this new association will be labelled and verbalized. Thus, the agent becomes aware of this new piece of knowledge: something 'intelligent' has been discovered. The adjective 'intelligent' relies completely on the knowledge of the observer (who could be the agent himself/herself). The 'new' association may already be known and, in this case, will not impress the observer, who will not use the term 'intelligent'; alternatively, it may be impossible for the observer to understand the new association because he/she lacks the necessary representations of items A and B. Therefore, intelligence is relative, dependent on the observer's knowledge. Language is not necessary to establish higher-level representations, only to become conscious of them. Therefore, an animal may show intelligence, but it would have trouble appreciating it.

6.3 Joy or pleasure

When the observer (who can also be the agent himself/herself) is not able to identify the goal-situation that the agent is trying to reach (and which generates the successive actions), then it is assumed that the agent's reason lies in a personal quest for joy or pleasure. In fact, the notion of joy only reflects the limited capacities of the observer [23]. The associative memory nature of the SOM hierarchy guarantees that, whatever the activation pattern at a given instant, the dynamics of the hierarchy system will direct it towards an existing memorized pattern. Memorized patterns make up only a tiny proportion of the overall number of possible patterns. The memorized information is therefore based on the most redundant patterns, i.e., the most shared cortical column activities: the smallest common activation pattern [24]. There is always a smallest common activation pattern behind any situation-goal, which, when not explicitly labelled, is named 'joy' or 'pleasure' for lack of a better explanation.

The notion of pleasure encompasses the fact that the agent will try to repeat the behaviours that have previously led to pleasure. A situation that exactly matches the smallest common activation pattern may be experienced from time to time. Since it is an attractor state (i.e., an equilibrium), palimpsest learning is very efficient in memorizing the actions that lead to this final state, facilitating its future reappearance.

6.4 Emotions

Motivation and emotion are linked, if only because emotion is often considered the (positive or negative) driving force behind motivation. An alternative definition of emotion is a "positive or negative experience that is associated with a particular pattern of physiological activity". This definition is incomplete as long as the positive or negative valence (neural) mechanism is not explained. A hierarchy of SOMs processes information at its own pace, which includes multiple neural steps, each with its own delays. In a number of situations, the time required to process this information may be dangerously long, and a faster way to take action would have been definitively retained through evolution.

The amygdalae (almond-shaped groups of nuclei located deep and medially below the cortex) are the only other brain structure with a cortical organization, and therefore represent input data on a (cortical-like) map. They are well connected to the sensory system (including the olfactory bulb), and send information to many locations, including the cortex (via the thalamus and hypothalamus) and motor neuron areas. Because their size is small compared to the cortex, the processing of information is *de facto* much faster. We hypothesize that the amygdala is an early warning system, able to stimulate immediate avoidance: a survival mechanism, quick to analyse situations and take action.

Avoidance actions are produced by the activation of 'negative' areas of the amygdalae. Due to their cortical-like organization, certain neighbouring areas generate a smaller-sized reaction and can therefore be considered 'less negative'. Moving further in this direction (over the amygdalae's map-like structure), there will be areas associated with 'no action', and then with actions opposed to avoidance (e.g., 'search for'). Let us define these areas as 'positive'. A few of the avoidance (and 'search for') actions may be genetically encoded, but learning also takes place. Therefore, whatever the particulars of the agent's life, some situations will trigger the negative areas of the amygdala, and others, the positive areas. The amygdalae's processing of the situations will not only result in direct actions, but will continue to diffuse through the various connected neural systems, including the cortex. The amygdala processing is thereby able to impact any aspect of the cortical processing, yet its actions will remain almost impossible to describe verbally. The use of vague terms such as 'mood' or 'fear' is clearly demonstrative of the great distance (in number of neural processing steps) between the amygdala and the cortical language maps.

7. Hypnosis, sleep and the placebo effect

A theory must be able to provide explanations for all the known phenomena that belong to its domain of competence. A theory about neural cognition must therefore describe the neural mechanisms implied by special psychological states, such as hypnosis [25], sleep and the placebo effect [26]. Despite numerous attempts, there is still currently no consensus on any of these questions.

7.1 Hypnosis

Since the world is continuous, there are – between any two successive instants – only minimal changes in the hierarchy of the SOMs that represent the associated situations. The prediction (cf. Section 5.3) allows to verify that these situation changes are coherent with all previously experienced and memorized changes (which includes the entire life of the agent). An error in these predictions will trigger an activation that will reach higher-level maps (exogenous attention). If, for reasons detailed later, prediction is inhibited, then there will be no reference points available to verify the validity (coherence) of a new pattern of activations. Whatever the behaviour that matches this new activation pattern, it will remain in place, unchallenged. This is the case, for example, when somebody follows the suggestions of a hypnotist on stage.

Hypnosis uses at least three different methods [27] to prevent the verification/comparison of the new pattern of activations (suggestion) with the prediction (control). First, the hypnotist is able to demonstrate that his/her predictions are better than the subject's ones, so that the subject 'voluntarily' (and momentarily) discards his/her erroneous prediction. This may be achieved with the use of ideomotor movements, usually unknown to the subject but predicted and evidenced by a specific exercise suggested by the hypnotist. A second technique involves 'confusion'. The hypnotist overloads the subject's cognitive capabilities until his/her pattern of activations is completely off-track; the hypnotist then suggests something easy to understand (which matches known patterns). This new pattern will therefore stick and become the (new) state of the system. A third technique consists in inducing a 'pattern break'. The hypnotist interrupts the subject right in the middle of a well-automatized routine, such as a handshake, and inserts a suggestion. Here, the routine belongs to implicit memory, which prevents any conscious awareness (i.e., no organized high-level pattern of activations). This explains why the new high-level pattern induced by the suggestion will never be challenged.

7.2 Sleep

The purposes and mechanisms of sleep are only partially clear and subject to substantial ongoing research. Hebb's law states that co-activation reinforces the common synapses, and conversely, that uncorrelated neurons will see a reduction in the strength of their shared synapses. Since efficient inhibitory synapses forbid (*de facto*) the activation of the target neuron, the efficiency of these inhibitory synapses decreases over time. However, since the plasticity of the inhibitory synapse has been demonstrated [28], a mechanism must exist that impedes or restores the efficiency of such synapses. Through Hebb's law, such a restoration is possible if both neurons (neuron A, and neuron B (the target of the inhibitory synapse)) are firing together. This is exactly what happens during slow-wave sleep (non-rapid eye movement or NREM sleep), when cortical electro-encephalography has measured high-amplitude waves at less than 3.5 Hz (delta activity). These depolarization waves reflect the coherent behaviour of a large number of neurons firing together and therefore strengthening the connections they share, in particular local inhibitory ones.

It must be noted that NREM sleep affects excitatory long-distance connections, reducing their efficiency, because long-distance activation is forbidden. These excitatory long-distance connections are the ones that link distant maps, that ground the associations or the 'intelligent' discoveries made during the day, and establish links between various aspects of reality. In order to smoothen the effects of local (inhibitory) reinforcement, NREM sleep is followed by REM sleep (also known as paradoxical sleep), during which activity looks very similar to that of the awake state. REM sleep activity involves replaying the day's activity, only about 20 times faster, and not in the same order [29-30]. During the night, NREM and REM sleeps follow each other, so that when the subject wakes up, inhibitory connection strengths are replenished, while excitatory long-distance connection strengths are maintained.

This model of the neural basis of sleep [31] explains why cognitive performance levels fall during the day. In fact, they are related to local inhibition efficiency between cortical columns. In the morning, efficiency is strong and guarantees that only one cortical column is activated at a time (i.e., no neighbouring columns). At the end of the day, activation on an SOM may involve several neighbour columns, which results in a fuzzier representation of the situation, and a less precise behavioural response. This also explains why every animal must sleep, why sleep *must* occur (under penalty of death), why one needs a recovery sleep after staying awake longer than usual, and why sleep debt results in diminished high-level cognitive functions.

7.3 The placebo effect

The placebo effect has been controversial throughout history, and still is; this is a sure sign that it has not been understood. Today, placebos are considered unethical despite their proven healing ability. A placebo is a substance (e.g., a sugar pill), or a (sham) procedure, which should have no action since it "is objectively without specific activity for the condition being treated" [32].

Plenty of effort has been invested in attempting to prove that placebos are, or are not, effective under a tremendous variety of health conditions. Tests have even been conducted on animals, such as dogs, and turned out positive [33]. The results show that the placebo effect is highly variable in its magnitude and reliability, and depends on the form, colour and price of the placebo, and on the country. One individual may respond to a placebo, while another may not. Studies attempting to relate this difference to the personality of the individuals remain inconclusive [34].

Evolutionary medicine – the goal of which is to understand why people get sick – points out that many of the conditions we prefer to avoid as much as possible (such as fever, pain and behaviours related to sickness) are in fact symptoms of the body's response to infection or injury, and should not be fought. These symptoms have neural causes, either directly or indirectly, through the (neural) activation of the endocrine and immune systems. Having neural causes, these conditions can probably be stifled by another neural activity pattern. High-level maps encode the understanding that a pill (placebo) improves one's condition, drawing on previous experiences with effective pharmacological substances, or previous descriptions of their efficacy (either by a trusted person, or direct-to-consumer pharmaceutical advertising (DTCPA)). This (high-level map) coding represents a better state of health. It synchronizes with low-level map activation patterns through backward connections (described in Section 5.2). The low-level activation patterns act upon the various systems, in order to bias the condition towards the expected one. The clearer the description one has of one's future improvement, the greater the placebo effect. The recent increase in the placebo effect among the US population can be linked to the legalization of DTCPA in 1997.

8. Autism, Alzheimer's disease and schizophrenia

Diseases such as autism, Alzheimer's disease and schizophrenia represent test cases for the explanatory power of the TnC. Taken together, they extend throughout a large spectrum of the population: autism is generally diagnosed early (in 18- to 24-month-old children), affects four boys for every one girl, and is displaying an increasing prevalence (2.6% of the 18- to 24-months-old-children in 2011 in South Korea); Alzheimer's disease primarily affects senior people (one in ten at 60 years of age; one in four at 80 years); and schizophrenia is typically diagnosed in young adulthood, and affects a little over 0.5% of the population worldwide [35]. Experiences associated with schizophrenia, and related categories such as paranoid delusional thinking and auditory hallucinations, are observed in an attenuated form in 5-8% of healthy people [36].

8.1 Autism

The diagnosis of autism is based on behaviour (i.e., not cause or mechanism [37]), with typical symptoms including impairments in social interaction, impairments in communication, restricted interests, and repetitive behaviour. LeBlanc and Fagiolini have proposed that alterations in the expression and/or timing of critical-period circuit refinements in primary sensory brain areas may significantly contribute to the autistic phenotype [38]. During a critical period, the neuroplasticity of a neural circuit (such as a cortical map) is improved, allowing for quick organization. Outside of these critical periods, neuroplasticity is impeded; it may still exist but not at the same scale. This is in accordance with a hierarchy of SOMs, with each level starting to organize as soon as the previous levels are organized. A disruptor, acting at any level, will dramatically impact higher-level performance. In the case of face-processing impairment, one of the most studied items in autism, Vlamings et al. have shown that lower-order visual deficits could impair higher-order visual processing of faces [39].

Kuhlman et al. have reported the induction of a new critical period, able to restore ocular dominance plasticity in the primary visual cortex [40]. This ability to interfere with the time course of critical periods may become a major tool in autism therapy. Repetitive behaviours are another reported characteristic of autism. The TnC states that, if the situation-goal that generates the behaviour is not correctly extinguished when the goal is achieved, the behaviour will start again. The failure to wipe off the situation-goal may be due to unbalanced excitatory-inhibitory networks [40] (i.e., failed map self-organization).

8.2 Alzheimer's disease (AD)

AD is a neurodegenerative disorder with no cure. Mental stimulation [42-43], exercise and a balanced diet have been reported to delay cognitive symptoms. AD is characterized by two factors: neural death and senile plaques. Neural death may reach as much as 50% to 70% in certain brain areas before cognitive symptoms allow for the diagnosis of the disease. This is a strong demonstration of the efficiency of neuroplasticity. The senile plaques of amyloid beta prevent electrical conduction, negatively impacting long-distance excitatory connections. The loss of autobiographic memory is today the major element to suspect AD. The TnC states that autobiographic memory is the most fragile (see Section 3.1), since the unity of remembered experiences requires time and space indexes. Interestingly, AD patients are no more prone to the placebo effect. This could stem from their inability to predict/visualize a healthy state for themselves, which is a function of autobiographic memory.

8.3 Schizophrenia

Schizophrenia is a very particular disease, with episodes of psychosis that last several weeks, separated by longer periods (several months) of recovery. The TnC describes 'personality' as the set of fixed (or constant) situation-goals among high-level SOMs (cf. Section 3.3). The TnC hypothesizes that an excessively small radius of inhibition around the cortical columns may result in a larger number of situation-goals, leading to antagonistic goals (i.e., incompatible goals). Since the activation generated by a situation-goal only stops when the goal is achieved, the patient will experience a higher level of global activation, which may lead to illusions, cognitive impairment or catatonia. Illusions are 'abnormal' activations, but they cannot be differentiated from normal activations (which is the reason why they should not be dismissed, as advocated by May [44]). Catatonia is the result of an incapacity to take action. The patient's personality (Section 3.3) has no situation-goal that stands out from the mass, and he/she is therefore incapable of acting.

The success of cognitive behavioural therapy (CBT) in schizophrenia [45-46] is based on its goal-oriented, explicit systematic procedures. CBT offers training to the 'personality' maps by defining new situation-goals, and providing numerous rehearsals to anchor them. It creates strong enough situation-goals to decrease catatonia and, by favouring a reduced and limited number of situations-goals, reduces the frequency of hallucinations.

The efficiency of antipsychotic medication (which blocks dopamine function) can be explained as a reduction in the global activation of the system: fewer situation-goals are active at any time. This also explains why antipsychotics have no effect over catatonia symptoms, and why, by reducing the speed of activation, they impede cognitive performance.

9. Building an intelligent and conscious robot companion

The TnC states that 'intelligent' is a qualification given to an agent (which can be ourselves), as soon as a new association is made that includes verbalization maps. The TnC also states that automatic verbalization provides a strong illusion of consciousness (to all observers, including ourselves). For a robot to be considered 'intelligent', it need only be able to show new associations to humans – associations that can be considered 'clever'. A robot need only be able to verbalize its internal states (i.e., its cortical column activations) to appear 'conscious'. In order to do so, the robot's hierarchy of SOMs must code information that we – humans – will understand. These maps must be organized by data that belong to our 'world' (i.e., colours, smells, sounds, speed, size, etc., must all agree with our human sensing abilities). This requires that the robot's representations of the world must make use of equivalent sensors. For the same reason, the robot should also be of similar size, strength, shape, etc., to a human. It should also be 'humaniform' (i.e., with legs, arms, head, bilateral symmetry, etc.). These constraints on the robot's body structure must be complemented by similar constraints relative to its internal clock speed (i.e., identical to that of a human when speaking, listening and thinking).

Using the TnC, an 'intelligent' robot's cognitive abilities should be close to those of a human; however, in order to achieve the same (self-)organization, this robot needs to benefit from the same learning data. It must be 'robot-sat' exactly as a baby is – a humaniform shape will certainly add to the necessary anthropomorphization [47]. One should also be prepared for several years of daily training before it is able to achieve child-level cognitive performances, several more years for teenager cognition, and several more years before this robot recognisably behaves as an adult. It may never clearly demonstrate 'intelligence' by teaching humans something they don't already know, but how many humans qualify for this?

The typical questions concerning super-intelligent robots gone wrong, such as in the case of *The Terminator*, are not relevant here, since the robot brain (just like the human brain) will only represent its experienced situations. Having been educated within human society, such a robot will be no more than 'human'. In order to develop a super-robot, one must be able to provide it with the required ('super') training data. A potential solution to this issue is to have the robot live and learn for a very long time, far exceeding a normal human lifespan.

Section 7.2 explains why such a robot will not require sleep (its local inhibition strengths will never change), which may help cut its learning duration by half (it could experience the world and human society both day and night). However, it would seem difficult to accelerate its learning any further. We don't know of any solution concerning how to use several robots in parallel and to merge their individual learning from time to time [48]. The distributed representation of the situations over the whole hierarchy of SOMs forbids it.

Today, commercially available humaniform robots exist, with sensors and actuators that match human capacities to a certain degree. However, their computational power is too limited. The TnC estimates the necessary cognitive units to be about 160,000, with an update frequency of about 25 Hz. This does not take into account the processing at the sensor locations, such as the eyes (100 millions pixels, with only 1 million fibres leading to the brain), but dedicated hardware are commercially available that implement similar rates of data processing (e.g., neuromorphic chips). The computational requirement for a TnC-based robot is only about 4 GFLOPS ($1.6\ 10^5 \times 25 \times 1000$), assuming 1,000 connections per cortical unit. This could easily be provided by a few Intel Pentium 4 microprocessors, which could be WIFI-connected to the robot.

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