Anticipative coordinated cognitive processes for interactivist and Piagetian theories

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Abstract. This paper presents a model of intelligence based on principles introduced by Piaget and the interactivist framework. It focuses on embodiment and sensory-motor aspects of the mind but copes with general issues such as regulation, accommodation to noise and variability or synchronization of the agent internal dynamics with the environment. The proposed evolutionary and constructivist theory is illustrated by a real-time rhythm recognition program and goal-reaching algorithm, both based on prediction and assimilation.

Keywords. interactivism, Piaget, assimilation, anticipation, regulation, rhythm, goal-reaching

Introduction

Though most of the work has still to be done, we aim at understanding and modeling the fundamental principles that make cognition possible. Taking inspirations from biology, psychology or philosophy, we try to validate hypotheses by implementing them in computer programs. Even if they are no proof of the plausibility of such theories for natural intelligence, they still allow us to refine the theory by adapting incorrect assumptions. By developing a solid basis for a general purpose artificial intelligence, human performance capable machines might follow in the future.

In this view there is no need for a robot or an application to go much faster than any living being on the same specific task, performance being better accounted in terms of adaptation and adaptability. Indeed low level sensory-motor activities, most current systems are unable to perform, require synchronizing with the environment, respecting correct timing and physics laws. Since we are concerned with such kind of issues, we define and evaluate our progress by applicative achievements reflecting a global coherent framework. Integrating aspects from various fields of science and trying to match evo-

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lution might not be necessary to reach a form of artificial general intelligence. Nevertheless analyzing or comparing the structure and functioning of organisms may help in producing robust adaptable autonomous systems.

Robots navigating in real environments face complexity, unpredictability, noise, electronic or mechanical imperfections, time delays and constraints. Thus, developing on robots is the perfect ground for testing adaptability; nevertheless simulations allow drastic parameters changes at will as well as environment customization. Moreover computer programs can be speeded up to monitor data evolution or down to analyze situations, produced in many versions at a fast pace and low cost. Therefore we have chosen to model simple behaviors, testing individual or coupled principles, in simulated environments with close to real-time real-life dynamics. Though artificial worlds and agents may possess only a few degrees of freedom, the complexity lies in the interactive and continuous nature of processes emerging from their coupled dynamics.

We believe in a philosophical naturalistic stance [1] as developed in the interactivist framework [2] or enaction paradigm [3]. Part of the forthcoming detailed applications are also based on Piagetian concepts such as assimilation and accommodation, introduced to account for the development of children during the sensory-motor period [4]. Several teams throughout the world capitalize on theoretical assumptions from the same background and target outstanding applications showing human level of cognition. However our goal is to go into the details of a coherent theory, explaining the development of an agent by coordinating action and perception through learning and coupling with the environment. We will therefore present the approach by detailing its main features then introduce explanations and applications targeting particular subjects of interest for artificial general intelligence: synchronization, use of tools, coordination, goal-reaching and unsupervised learning.

1. Framework and specificities

The main difference between the interactivist framework and classical symbolic and computational approaches, which have been dominating artificial intelligence and cognitive science for decades, is its commitment to a process metaphysics [5]. Many fields in science have progressively shifted from substance to process theories, for instance to account for quantum physics specificities. By moving from a list of properties and atoms to interactions and processes, the so-called ‘symbol grounding problem’ [6] is dissolved: novelty is explained in terms of emerging dynamics of coupled systems instead of combinations of a limited set of symbols. Representations and concepts are then functional and implicit; change becomes the default and stability is to be explained by compensatory influences or rhythmic cycles in a network of processes (or more generally in terms of attractors in the dynamical systems language).

Philosophers such as Bickhard or Dennett also support a continuously increasing complexity and progressive appearance of cognition, intelligence and consciousness through species evolution [7]. In the end there might only remain a weak coupling between the body and higher functions of cognition, but exploring the differentiations and emergence of living beings may be the first step to select relevant principles to design truly intelligent architectures. Additionally, this approach allows an incremental construction of agents with milestones set on the turns of past evolution. In a way it is similar to the goals targeted by the subsumption architecture [8] though we rather look into refining the minimal set of principles at the lowest level before combining activities.

Although numerous processes might interact to produce an emergent behavior, the agent is neither an integrative nor hybrid system: we argue that unified principles can be applied for any modality and at any level. Of course the system might benefit from the full potential of classical artificial intelligence techniques or signal processing algorithms, but they will remain at the interface to ease the interaction with the environment. The homogeneity in structure and communication allows merging independently developed subsystems without having to implement the way they will combine: synchronization and coordination principles ruling the local dynamics extend to the global emergent system.

2. Principles

We will now describe the principles our research is focused on, in a sequence following the history of life evolution, even if many principles are deeply intertwined or might overlap in time.

2.1. Regulation

Regulation was already present in the very first living organisms, and sometimes even in non living phenomena. Animals are good at coping with variability as long as life is still possible, by regulating their behaviors and accommodating to environment variability. Computers are not: most programs show little sign of adaptation and hardly deal with 'continuous' changes in their inputs, even when introducing many other concepts we think useful for cognition as in Drescher's model of Piaget's schemes [9].

Regulation covers several meanings and goes from muscle fibers control to complex path planning. Even for what seem to be fairly simple contractions, regulation has to deal with strained cells, the effect of gravity depending on the movement, nutrient levels and a slew of additional factors. When shifting to complex bodily movements, regulation goes far beyond recruitment and homeostasis. Merleau-Ponty described how joints of the whole body get involved while trying to grasp an out-of-reach object [10]. Monitoring and controlling all these parameters in a centralized way is illusory, and more details will be given in the goal-reaching section of the paper.

More surprisingly, living organisms are also able to metaphorically map behaviors to different modalities, as long as the interactions keep their structure and temporality [11]. After birth, there is no clear differentiation between sensors (myelinization is for example not complete) and even after learning, the plasticity of the cortex can deal with dramatic changes in the brain-sensor coupling [12]. Regulating actions to cope with temporary hindrance or life lasting infirmities is of a rare complexity but is naturally performed by animals. Similarly, taping a known rhythm, humming it, singing it, nodding it or expressing it by any mean is something most humans can do.

2.2. Assimilation and far from equilibrium dynamics

In Bickhard's genesis of cognition, far from equilibrium dynamical systems maintain their function by actively interacting with their environment. The very same behavior is found in the theory of autopoietic systems, illustrated by a simple cell model called the tessellation automaton [13]. This form of survival and autonomy might be a good minimal candidate to define life, but may simply be interpreted in terms of assimilation. The concepts of assimilation and accommodation in Piaget's terminology refer to the forces that make processes subsist. An interactive process is defined by its function and relation to its environment. It needs to adapt to the situation, coping with the uniqueness of each moment in its history, either by neglecting differences or by modifying its own structure to match specificities. Such kind of processes will also be referred to as schemes in the following paragraphs.

Schemes might be passive, only synchronizing with external signals, but most of them affect their close environment by acting on it and increase their assimilation level in return, turning them into actors of the overall dynamics. Assimilation might well be enhanced or the associated process 'activated' by environmental cues independently of the agent's focus and decisions, but processes will influence or control actions depending on which level they assimilate the situation. For example, a known but unattended object appearing in the field of view might raise the assimilation level of a visual tracking scheme. The agent might progressively follow the new target when letting the scheme get control over eye movements; this is what happens when someone wanders and let attention focus on any salient feature encountered in its environment.

Any internal, sensorial or motor cue that can be assimilated by a particular scheme might increase its influence if conceived as an attractor in the global dynamical landscape of possible actions. For human beings, a simple evocation when thinking or dreaming is often enough to trigger a flow of activity spreading through the mind. The propagation interacts with the structure and current activity of the network, following thoughts associations, memories or sequences [14].

2.3. Interrelated parallel processes

As cells or organs interact in multicellular organisms at biological level, society members live their own lives but participate in several organizations. The same applies for interactive processes, which are constituents of the agent. Every scheme continuously tries to assimilate its environment, sometimes with success but often without being able to synchronize with inadequate situations. What matters at the global agent's level, is not the amount of adapted processes, but their existence with a sufficient level of activity to guide actions.

This massively parallel structure is compatible with redundancy, loss and creation of new schemes, each of them influencing the overall dynamics without being necessary to the emergent system. Several processes might perfectly synchronize with the same situation and even promote the same actions, not hindering each others. One might even be a more specialized version of another, allowing a progressive recognition. For example what might initially be assimilated to a fast moving object by roughly tracking a shape, may successively become a bird then an eagle. Associated schemes will be partially activated by the indirect influence of the general process, promoting compatible though more precise actions, like saccadic or smooth eye movements to check for particular features found on a bird but not on an airplane, found on an eagle but not on a crow.

Schemes not only indirectly interact through correlated actions on the environment but may also synchronize and coordinate with other related processes by propagating or modulating their activity. This aspect and its implications for goal-reaching behaviors will be detailed in the corresponding section. Whatever the underlying principles ruling the interactions are, only the relative strength of the various attractors coexisting in the dynamical landscape matters in the end. This relativity removes the need for thresholds and even a broad weak activity might strongly influence the agent's perception if the context prevents any excessive stimulation. Internal activity might therefore overcome or replace the real sensory flow, making the agent subject to illusions or dreaming.

2.4. Anticipation

As soon as animals started to explore complex and unpredictable environments, genetics could no more select hardwired adapted reflexes for all situations and the risk of dying from an unadapted behavior increased. Therefore being able to learn from past experience and anticipate consequences of actions became crucial. Moreover by living in a future-oriented manner, organisms could integrate timing in their activities. This is particularly useful for 'distant' senses such as sight, to anticipate the approach of a predator, but also to account for inertia in complex metabolisms, nutrients being necessary for systems to function before a burst of activity. This shift from reactive systems to anticipative systems is an elegant solution to delay problems in any sensory-motor task, but also ease the understanding of planning and similar future-oriented phenomena.

Anticipation combined with assimilation introduces a normative aspect not present in frameworks requiring a supervisor stating whether the agent is right or wrong [2]. By acting on the environment and anticipating consequences, a scheme expresses a simple form of knowledge. The action may not be performed or anticipations not confirmed because of environmental constraints (obstacles hindering the movement or hiding features) or conflicting schemes (promoting different actions). In any case, the process will lower its assimilation level, i.e. its activity and strength as an attractor, and let other schemes decide for more adapted actions. In fact, the assimilation level symbolizes confidence in the behavior relatively to the current situation. Assimilation and the intrinsic inertia of schemes account for the object permanency appearing during child development. For example, the ability to follow objects even when partially hidden or moving behind a screen has been extensively studied in literature [15]; it might be explained by an insufficient decrease in assimilation during occlusions, keeping the agent focused on the anticipated trajectory.

When humans are faced with daily objects that are designed in such a way they become hardly recognizable, previously acquired schemes, perfectly adapted to standard pieces of furniture, still apply. As long as it can be comfortably sat on, a chair will be assimilated as a chair, whether it has a round shape or lacks a leg. The same was experienced by Tsien and his colleagues with mice lying in dishes or any material containers correctly satisfying the anticipations of a 'nesting' behavior [16].

3. Application to rhythm recognition

We have designed in the past a computer program which uses these principles for recognizing musical rhythms in an unsupervised way [17]. A human user had to rhythmically strike a single key on the keyboard. The user was free to speed up or slow down, stop and restart at any point of the score. Moreover humans are generally not able to keep a perfectly regular pace and make mistakes even in a rhythm they decided to teach to the program, so it had to accommodate to speed, phase and imperfections in real-time (figure 1). Correctly recognizing and synchronizing with the rhythm involved anticipating the following beats, and the score was dynamically displayed and updated on the screen. We perform similarly when tapping with our foot while listening to some music. Notice that, given the slow biological feedback loop from ear to foot, a good synchrony is impossible to achieve without actually already knowing the rhythm and anticipating the beats. At the beginning the program would only know the binary rhythm, but progressively differentiate new rhythms, adding new notes or changing their length.

In addition to implementing and testing several principles, this program helped in realizing aspects that follows from assimilation: sensory signals must be assimilated by a process to be perceived and interpreted, novelty must be close to something already assimilated to be learned. Though an utterance in a totally unknown language would be assimilated as a sound and maybe as independent syllables, the rhythm and structure of sentences will not get caught without proper interactions with speakers. Assimilation may also explain how many magic tricks work: by focusing the attention of the public on distracting aspects of the situation, schemes tracking objects might never reach the sufficient level of assimilation and get enough control to make the agent detect a blatant disappearance [18].

Since a myriad of anticipated features combine into a scheme temporally strengthening its activity, there is often no need to confirm all the predictions. Except when the context is ambiguous enough and a decision has to be made to select a particular scheme, the agent will keep switching between behaviors or thoughts, as long as the emerging behavior remains adapted. Our inability to perceive stunning changes as well as unattended events in our environment when concentrating on a task is called perceptual blindness. It is integrated in several theories and accounts for several previously described properties of perception [19].

External influence of the environment on the agent's dynamics is often described as bottom-up or reactive depending on the field. It has to be related and compared to the top-down anticipative activity of internal processes. In the introduced rhythm program, external activity of the human user influences the learning algorithm and guides current recognition, successive sessions leading to totally different differentiations. At the same time, internal activity structures the perception, coping with noise, missing notes and

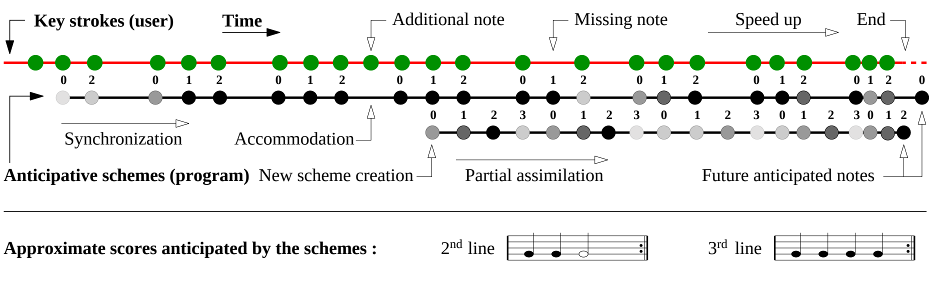

Figure 1. Annotated screenshot of the rhythm recognition program at the end of an interactive session. The first line corresponds to the unconstrained user input with each dot representing a single stroke. The additional lines reflect the knowledge of the agent, constituted by schemes anticipating future strokes in real-time. The program correctly accommodates to mistakes and pace variability. A genetic algorithm also generates differentiated schemes to accommodate to slightly different rhythms.

varying tempo. It also determines what the artificial agent is capable of and how much it can interpret. Although it is certain both interact and synchronize, what is called internal, external and the delimiting border is quite fuzzy. Interactions between top-down attention and bottom-up perception of salient features may account for the distinction between subliminal, unconscious and conscious processing [20].

4. Relation to the environment

This distinction between the inside and the outside, self and others, has recurrently been discussed by philosophers and is linked with embodiment in our view [21]. We must precise beforehand that we do not presume the body has to be natural (developing with mind during philogenesis) but think robots will be able to grow an implicit knowledge about their body by a short coupling history with their environment (ontogenesis). Still interacting with a coherent environment is necessary not only to learn regularities, but also to develop natural and intelligent behaviors.

The notion of environment is relative to the system, always constituted by the sensing and actuating capabilities it possesses. Environment is limited to a local extra-cellular space when considering cells exchanging molecules through their membrane, but embraces hormones for long-range internal communication between organs and distant object perception at the organism level. The organization and relations between dynamical systems eventually lead to the assimilation of a wide environment at the person level, including other individuals, technology or even society. When climbing several steps on the ladder of emergence, the coupling becomes weaker [22], as for the relation between higher values in human psyche and body metabolism.

Each process has a subjective view of the objective world and only interacts through perceptions and actions useful to its function. Variables and internal activities at a given level of emergence might well become inaccessible or part of the environment for a higher level system integrating the activity of hundreds of such lower level processes. Consciousness may result from the reflexive activity of a dynamic cluster of processes, modulating the activity of 'lower' unconscious systems. Tasks that require conscious attention at first, as when repeating moves specific to a newly practiced sport, progressively become automatic, to the point where it becomes impossible to decompose the skill into smaller pieces. Once mastered, the nearly autonomous skill can only be monitored and modulated by acting upon its environment.

This description makes even fuzzier the limits of the agent, though several researchers already consider the cognition is out there, 'the world being its own best model' as Brooks underlined in *Elephants don't play chess*. Interacting with the environment is like discussing with it: acting is like asking a question, and perceiving like listening to the answer. Communication is intentional and goal-oriented: the agent is willing to satisfy its anticipations and come to an agreement but adapts its behaviors to the environment responses by introducing cooperative arguments.

Using tools is only a question of correctly integrating them into the agent dynamics by interfacing them with other behaviors. If coupled enough to be indistinguishable from pure abstract cognition, always playing a role in the resolution of issues and discovery of solutions, they might be part of the intelligence. A similar relation exists between speeches dealing with abstract concepts and associated spontaneous body movements, contributing to the understanding of notions grounded in sensory-motor behaviors [23]. If tools had to be put somewhere, it would be between purely internal thoughts and clearly external laws ruling the physical world.

Perfectly using a tool has little to do with knowing how it works, as the archerfish shoots insects from distance without mastering fluid mechanics, gravity or refraction laws. The approach is rather similar with web services applied to grid computing: the end-user ideally just learns how to send requests, without caring about the algorithm used to solve his problem. The various libraries that may fulfill the request are articulated to the global system defined by its function. Back to organisms, a human body replaces its skin cells without losing its integrity or nature.

5. Internalized activities and goal-reaching

By propagating their activity to related processes, schemes whose assimilation level is not high enough to control the evolution of the situation still influence the internal dynamics. We will refer to this activity as 'internalized' although schemes might partially synchronize with the environment. In this case, anticipations are confirmed by a weak evocation from other processes. In a recently developed computer program designed to model goal-oriented coordination of schemes, we introduced activity propagation as the main characteristic to account for path planning. It proved functional and efficient in coordinating schemes in a 2D navigation simulation with dynamical goals.

Whereas assimilating schemes are reduced to their simplest expression in the current version of our demonstration program, the resulting behavior matches the basic expectations of a general navigation algorithm. A scheme consists of a contextual situation including sensory and motor information, an anticipated situation with the same structure and a real number reflecting its assimilation level. Such links between potentially perceived states act as shortcuts for the agent to project into the future. A chaotic network consisting of all the interactive schemes shapes the dynamical landscape. Though schemes remain the only form of representation, their heterogeneous distribution within the network accounts for the various needs in terms of precision and specialization. The relative weights reflecting schemes assimilation also allow continuous changes and regulation in the overall dynamics. In the field of color perception, red and yellow would

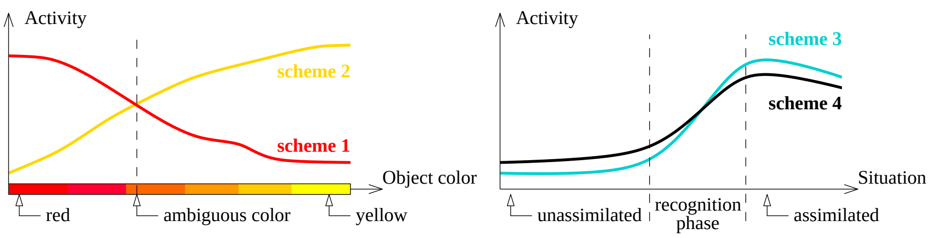

Figure 2. Conflicting or synchronous assimilation of schemes. (left line chart) Schemes assimilate different colors, potentially involving complex interactions. The number and repartition of such schemes might greatly depend on culture and environment. Whatever the basic set of colors is, intermediate colors will be differentiated by the relative level of assimilation of existing schemes. (right) Schemes 3 and 4 may simultaneously assimilate different correlated aspects of the external dynamics, as lip movements and associated sounds during an utterance. One might also be more specific than the other or just redundant.

for example be assimilated by two schemes, therefore creating distinct implicit classes, though orange might be perceived as an intermediate color, partially assimilated by both of them (figure 2). Color perception might not just be the acquisition of cones activity like reading a value, but a complex process involving changes in the reflected light depending on object and observer's positions [19].

The decision to go in a given direction to reach a goal is often taken without even being able to perceive the target. It is not only unrealistic to anticipate the consequences of all possible actions, but impossible to predict what the exact evolution of the dynamics will be. In our approach, goals consist in impeded schemes partially assimilating the situation but unable to fully satisfy their anticipations. If they reach the highest levels of activity in the network relatively to other processes, they will shape the overall dynamical landscape. Propagating their activity and increasing the assimilation level of compatible schemes, implicit chains of interactions will connect the current assimilated situation to the goal, guiding the agent toward it (figure 3).

Anyway, though the agent might imagine obstacles or intermediate steps, it will only be able to truly satisfy the associated schemes by acting and confirming its predictions, coping with unpredicted events or variations as they occur. From a car driving perspective to illustrate the phenomenon, some 'abstract' schemes would connect distant cities and diffuse their activity at their extremities. The activity is attenuated with distance to reflect the decreasing degree of assimilation. Simultaneously, a quantity of schemes requiring fast interactions with an ever changing perceptual world would account for traffic signs reading, braking or turning behaviors. Though all the schemes have the same structure and function, the difference lies in the scope of their influence, i.e. the range of the resulting shortcuts.

Although several schemes might perfectly assimilate the current situation, those coordinating with the goals will attract the agent slightly more. This bifurcation in the dynamics will progressively lead to a higher assimilation level of the chosen schemes, which will in return increase their control as long as their anticipations are confirmed. Additionally, goals are relative to a given scale and might be simply considered as local attractors when shifting to more global behaviors. Such a stance toward goals contrasts with reward maximization and similar algorithms supposing a clear cut between evaluation and cognitive processes [24,25] or the fixed hierarchy of Brook's subsumption architecture.

6. Learning and evolution of the system

Learning may start with sensory-motor contingencies as immediate interactions with the environment. By a permanent tendency to assimilate its environment, the agent will generate new schemes to better account for specific situations or for complex regularities. The notion of object, concepts and symbols will then arise from schemes internalized activity [26], freed from the high variability and limits of the physical world. Indeed, by aggregating numerous local dynamics subject to rapid changes into statistically more stable schemes, the agent will recursively build an implicit hierarchy. Top elements will present a temporal and spatial stability characterizing abstraction, even in noisy environments disturbing low level synchronization, or complex situations where motor control switching between conflicting schemes is required [27]. When looking at a visual scene,

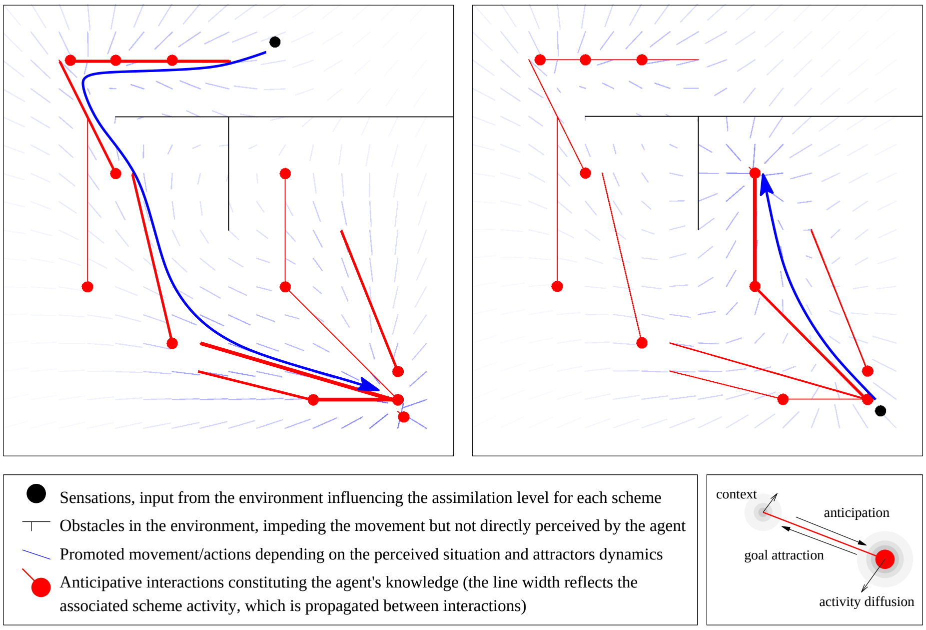

Figure 3. Goal-reaching dynamics illustrated on a screenshot of the 2D navigation program. Lines with dots correspond to known moves in the environment, the black dot to the current position. (left screenshot) Although no global trajectory is computed (a posteriori superimposed arrow), the agent follows the activity gradient resulting from the combined assimilations of all schemes. (right) Even when keeping the same structure, changes in activity lead to a different attractor and a totally different dynamics.

we perceive a structured world composed of permanent objects though the optical flow hitting our retina is totally renewed for each slight rotation.

Learning does not start nor end, neither can it be dissociated from the overall functioning of the agent. Learning improves the agent's knowledge in real-time by coping with previously unassimilated elements; it continuously modifies the dynamics but does not hinder it. Though memory might get reinforced by running the same schemes again and again, particularly during sleep [28], past memories also gets modified by present events. What appears singular and unique the first time it occurs gets progressively generalized when encountered again. Whereas specializing schemes too much results in an inability to take advantage of past experience in similar contexts, extreme generalization leads to confusion and unadapted behaviors. Thus an agent has to find the golden mean between assimilation and accommodation relatively to the tasks it has to perform.

Building multi-scale networks of interactions competing for assimilation not only helps solving this issue, but allows clusters of highly connected processes to emerge. These clusters, stabilized by activity propagation, might be the first step to escape sensory-motor limitations. Recognizing a 'restaurant' would be equivalent to staying in the network defining the concept while interacting with the environment. Visual interactions with the shop front, formalized communication with a waiter, arrival of the menu and selected meal dishes are all coherent with the standard 'being in a restaurant' behavior. Pubs, fast-food or self-service restaurants would be assimilated at a lower degree, but the concept would remain adequate as long as the agent would satisfy its anticipations and goals.

Even if activity might be initially bound to physiological needs, monitoring body indicators like hormones levels, most of the internalized activity in a human adult is only weakly coupled with biology. Abstract attractors in everyday life dynamics, like habits or higher values, may derive from simple needs such as thirst or hunger. Such physiological processes are genetically selected, hence can be considered as 'positive' behaviors for the agent's survival. Yet even obsessive-compulsive disorders, psychological addictions, self-mutilation or extreme sport practice could develop from the very same 'positive' behaviors. However, the need for direct perception and strong coupling with the body would be replaced by a recurrent autonomous internal activity relatively independent of metabolism regulations. For instance, assimilating the activity of others to its own schemes is a first step towards empathy. Nevertheless, processes regulating and stabilizing the basic functions of our organism would remain. Their overwhelming strength when unsatisfied is explained by the inescapable feeling of body signals: averting one's gaze makes threatening pictures vanish but thirst is not to be forgotten (figure 4).

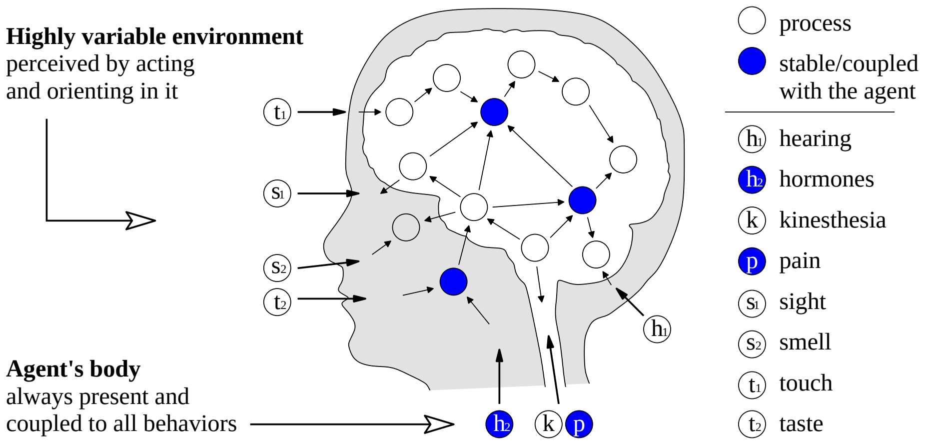

Figure 4. Evanescent and obsessive perceptions relative to the coupling with the agent. When the agent interacts with its environment, the flow from many sensory modalities might change drastically. Still internal sensations or the stable activity of some schemes will not be disturbed by such instant changes. Though a clear cut is drawn on the figure, a continuous range of couplings exists, defining a fuzzy limit between the agent's core and environment.

Perspectives

After the rhythm and coordination applications, we now aim at better integrating all aspects of our theories in a computer program encompassing a broader spectrum of phenomena. Particularly, though time is implicitly introduced in the navigation algorithm by the constraints and timing of the environment, speed regulation is absent. A good candidate would be a driving agent who could visually anticipate trajectories and act accordingly. Gaze control introduces sensory-motor conflicts between promoted actions, thus a good coordination of schemes would be needed. Alternation and regulation of behaviors are required to simultaneously track the road and look at traffic signs for example. This application opens up to another dimension, allowing many and even abstract extensions such as navigating in a city, respecting speed limits or avoiding accidents.

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