HOW TO INVESTIGATE THE *LIVING COGNITION*: AN APPLICATION TO DYNAMIC SIMULATION OF MENTAL ACTIVITIES WHILE DRIVING

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Abstract

This paper is dedicated to the "living cognition" issues, which concern the ability of a cognitive model to simulate humans' mental activities when dynamically interacting with the external environment. After having introduced the theoretical foundations of this approach, an integrative *COgnitive Simulation MOdel of the DRIVEr* is presented (i.e. COSMODRIVE). The central process that supports the *living cognition* in this model is the *deployment* of a *cognitive schema*, corresponding to the driver's mental representation of the driving situation as instantiated in the Working Memory. This dynamic visual-spatial mental model, defined as the driver's *situational awareness*, is used by the driver for perceptive exploration of the road scene, decision-making, anticipation and action planning, in order to interact with the road environment. This dynamic process of regulation is based on both *implicit* and *explicit* mental simulations and is illustrated through an example in the last section of the paper.

Keywords: Cognitive simulation, car driving, visual-spatial mental representation, dynamic cognition, implicit and explicit situation awareness.

1.Theoretical foundation of the living cognition

Although a familiar task of everyday life, car driving is however a complex activity that involves every levels of human cognition. Indeed, driving a car requires (i) to select relevant information from the environment, (ii) to understand the current situation and to anticipate its progression in the more or less long term, (iii) to take decisions in order to dynamically interact - via the vehicle - with the road environment and the other road users, (iv) and to manage owns resources (physical, perceptive and cognitive) in order to satisfy the time constraints of the task, inherent to the dynamic nature of the driving situation. The selective dimension of information collection is especially important as drivers cannot take in and process all the information available in the road environment. As we shall argue in this paper, this information is not selected haphazardly. It depends on the aims the drivers pursue, their short-term intentions (i.e. tactical goals, such as turn left at a crossroads) and long-term objectives (i.e. strategic goals, such as reaching their final destination within a given time), the knowledge they possess and the attentional resources allocated to the driving task. Information selection is the result of a complex process whose keystone is the driver's mental representation of the driving situation. Indeed, from their interaction with the road environment, drivers build mental models of the events and objects that surround them. These mental representations are dynamically formulated in working memory through a matching process between (i) pre-existing *operative* knowledge (Ochanine, 1977) and (ii) perceived information extracted in the external environment. They are formulated *by* and *for* the action, and they provide *interiorized models of the task* (Leplat, 2005). When driving, these representations provide 3-Dimensional (i.e. visual-spatial) models of the environment, liable to be mentally manipulated by the driver, in order to support anticipation through cognitive simulations, and thus providing expectations on future situational states. Drivers continually update these mental models as and when they carry out their activity. This dynamic process, based on both *implicit* and *explicit* mental simulations (Bellet et al., 2009), is the central focus of the "*living cognition"* (Bellet, 2010) as investigated in this paper. At a theoretical level, the living cognition is jointly based on three scientific traditions: (i) the *cybernetics* and the *human information processing* theories, (ii) the Russian *theory of activity*, and (iii) the *ecological approach of human perception*.

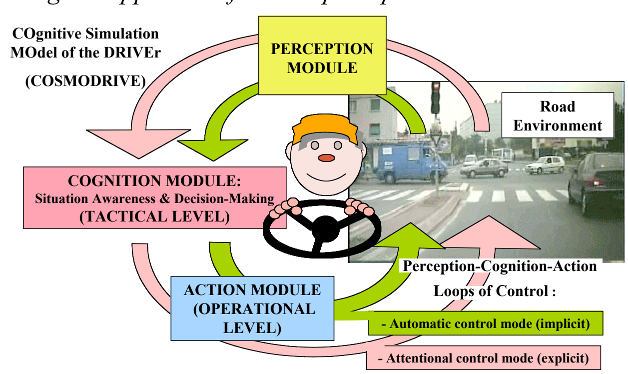

Figure 1: the car driving activity as a dual regulation loop

According to Wiener's *cybernetics theory* (1948), human can be defined as a self-adaptive system who interacts with the external environment through a feedback regulation mechanism. Humans' mental activities are then described as a black box owning information processing mechanisms, able to generate *outputs* from perceptual *inputs*, in order to adapt itself to the situation. As and when this cycle repeats itself recursively, the human cognitive system perceptually assesses the effects of its action on the environment, and then determines which new action is needed to achieve the expected state of the surroundings. This iterative process start again until this state-goal is obtained. Although cybernetics has finally introduced an epistemological break with the behaviorist approach in Psychology, the initial model proposed by Wiener was fully compatible with the Skinner's "S-R" approach, until the Pandora's black box was opened. However, with the development of the *human* *information processing theory*, the internal mechanisms implemented into the black box, like mental representations elaboration, reasoning, or decision-making, became the new central topics of the cognitive sciences. Nevertheless, according to the experimental method used in laboratory for investigating cognition in well-controlled conditions, the Cybernetics "loop logic" has been progressively lost for two main reasons. First, the experimental paradigm applied in cognitive sciences requires to artificially break down human cognition into several functions to be individually investigated. Moreover, and maybe more critical from the *living cognition* point of view, in-lab investigation of human cognition are based on repetitive measures collected for similar artificial tasks, in similar conditions. Therefore, the story must re-start after each new stimulus, as if it was a totally "new story", in order to allow the scientists to rigorously control the experiment. After each S-R sequence, the task is thus completed, without any expected feedback effect. Therefore, by using the experimental method, cognitive sciences ended up losing the notion of "cycle", however so important in the cybernetics *feedback* process supporting the dynamic of the living cognition, in favor of a sequential string of processes, from perception to action.

Like Cybernetics, the Russian *Theory of Activity* considers human operators through their dynamic interactions with the external environment. But in this approach, *Activity* is the starting point and the core topic of the scientific study of human cognition, because it is argued that activity directly structures the operator's cognitive functions. The fundamental postulate of the Theory of Activity is well summarized by Smirnov (1966): *human becomes aware of the surrounding world, by acting on it, and by transforming it*. From this point of view, human is not a passive cognitive system whose undergoes the stimulus given by the external environment. S/he is an active observer, with inner intentions, able to voluntary act on the world and to modify the situation by their activity, in accordance with their own needs. Indeed, behind activity *there is always a need, which directs and regulates concrete activity of the subject in the objective environment* (Leontiev, 1977; p. 88). Such a consideration, so essential in our everyday life as psychological subjects with needs, intents and will, has been nevertheless progressively forgotten by the modern cognitive sciences, when based on the experimental paradigm. Through laboratory experiments, inner needs and spontaneous motives disappear, as well as the dynamic "life cycle" of the natural living cognition.

The same criticism against the destructive effect of experimental method when applied to cognition has been formulated by Neisser (1976), through his *ecological approach of human perception.* Neisser's work was initially based on the *direct perception* theory of Gibson (1979), who postulates that some *affordances*, corresponding to properties of the objects, are directly perceived by the organism. By contrast with the Gibson "un-cognitive" theory of perception, Neisser admits the existence of mental functions, even if he criticizes the sequential vision of the cognition dominated the human information processing theory. In a synthetic way, Neisser considers perception as a skilled and iterative process. Like the Russian theorists of the activity, he argues that human are not passive receivers of perceptual inputs, but that they are *active* in the world, in accordance with their own motives, their abilities, and their expectations. His approach describes perception as a dynamic cycle focused on the relationships between pre-existing knowledge and the human information-gathering activity. According with this *perceptive cycle*, the perceiver actively explores the surroundings, and then constructs a dynamic understanding of the current environment. The mental structure that supports such processes of perception is described as an *active schema* of the environment, which is continually modified by the new perceptual information, and which also contains anticipatory expectations. This mental schema includes a *cognitive map* of the world, and therefore directs perceptual explorations of the environment, or prepares the mind for perception of anticipated events. It can be consequently considered as a kind of *control structure* of the perceptive processes.

2. An integrative model of the car driver

In this section, we would like to present a comprehensive model of the human driver, so-called COSMODRIVE (for COgnitive Simulation MOdel of the DRIVEr, Bellet et al., 1999, 2010), that combines in an integrative way the different theoretical approaches presented above. Several driver models have been developed during the last decades, even if the most of them are focused human's *performance* more than on *cognitive simulation* (for a discussion on this issue, see Bellet et al., 2007). One of the most advanced one is surely the driver model developed by Salvucci (2006), that is based on the ACT-R cognitive architecture (Anderson and al., 2004). Like COSMODRIVE, this model provides an integrative approach of the driver's cognition, by considering 3 components of (i) *control*, (ii) *monitoring*, (iii) and *decision making*. Cognitive abilities at the *monitoring* level are conceptually close to our approach of *mental representation* simulation, even if they are different from the computational point of view (ACT-R *chuncks* in *declarative memory* versus visual-spatial [3D] and dynamic mental models in COSMODRIVE). Nevertheless, the aim of this paper is not to theoretically discuss on driver models, but only to provide an illustrative example of the *living cognition*, applied to a very familiar task. The figure 2 provides a synthetic overview of the cognitive architecture of COSMODRIVE. The heart of the model are the drivers' mental representations of the driving environment, corresponding to the driver's *Situation Awareness* according to Endsley (1995) definition of this concept: *the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future*. These mental models are built in working memory. At the *tactical level* (Michon, 1985), they provide an ego-centered and a goal-oriented understanding of the traffic situation, including anticipations of the future changes of the current driving situation, liable to be mentally investigated by the driver at an explicit level. At the operational level, which generally corresponds to the driver's *implicit awareness* of the situation, driving activity is implemented through operative know-how for vehicle lateral and longitudinal controls (Bellet et al., 2009). This dichotomy between implicit and explicit cognition is well established in scientific literature, for example, with the distinction proposed by Schneider and Schiffrin (1977) between *controlled processes*, which require cognitive resources and which can only be performed sequentially, and *automatic processes*, which can be performed in parallel without any attentional effort. In the same way, Rasmussen (1986) distinguishes different levels of activity control according to whether the behaviors implemented rely on (i) integrated sensorial-motor reflexes (*Skill-based behaviors*), (ii) decision rules for managing familiar situations (*Rule-based behaviors*), or (iii) generic knowledge activated in new situations for which the driver doesn't have any experience (*Knowledge-based behaviors*).

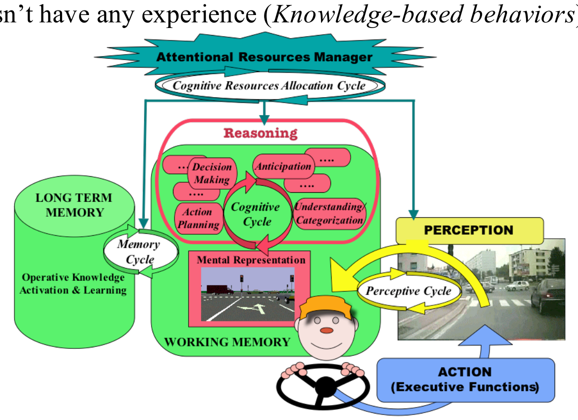

Figure 2: Cognitive architecture of COSMODRIVE

Four dynamic cycles regulate the internal functioning of the model. The *perceptive cycle* supports the human perception functions, allowing the driver to actively explore the road environment, according to their current needs and objectives (top down *perceptive exploration* process) and to integrate new information into their mental models (bottom up *cognitive integration* process). The *memory cycle* plays a central role for pre-existing knowledge activation (based on *categorization* and *matching* processes permitting to fit knowledge with the reality, Bellet et al., 2007) as well as in terms of new knowledge acquisition. The *cognitive cycle* corresponds to a set of *cognitive agents* (like mental representation elaboration, understanding, anticipation, decision-making, or action planning) which collectively handled the internal mental representations, in order to take appropriate decision and then, to act into the current environment. Lastly, the *cognitive resources allocation cycle* is in charge to dynamically regulate and control the life cycle of the driver's cognitive system, in accordance with the attentional resources that are currently available.

The central structure supporting to the living cognition in this cognitive architecture is the *working memory*. From this point of view, this architecture is directly inspired by the ACT-R theory (Anderson et al., 2006). However, the working memory of COSMODRIVE merges both *procedural* and *declarative* memories, and comes more from the *operational memory* concept of Zintchenko than from the Baddeley's *working memory* model (1986). For Zinchenko (1966), the operational memory is a structure whose main function is to *serve the real needs of the activity*. Thus, it is a transitory rather than permanent memory. However, it should be distinguished from a short-term buffer limited in storage capacities, in so far as the information it contains remains available for as long as the task is performing (for several hours in some cases).

Through COMSODRIVE approach, car driving is modeling as a dynamic process of interaction between the driver and the environment through a dual iterative regulation loop, supporting the living cognition. In accordance with the *Cybernetics theory*, human activity is defined here as an continuous loop of regulation between (i) *inputs*, coming from the road environment, and (ii) *outputs*, corresponding to the driver's behaviors implemented into the real world via the car, which generate (iii) *feedbacks,* in the form of a new inputs, requiring new adaptation from the driver. From this general point of view, the first iteration of the Perception-Decision-Action regulation loop corresponds to the moment when the driver starts up the engine, and the last iteration comes when the driver reaches the final trip destination, and stops the car. In accordance with the *Human information processing theory*, human is not described here as a closed black box, but as a set of perceptive, cognitive and behavioral functions allowing the driver to dynamically regulate their interactions with the surrounding environment. In terms of cognitive activities, mental representation of the driving situation plays a key-role in the cognitive system functioning. This mental model, based on perceptive information extracted into the road environment, corresponds to the driver's awareness of the driving situation, and therefore determines directly all their decision-making concerning the relevant adaptive behaviors to be carried out in the current driving context. In accordance with the Russian *theory of activity*, this mental representation is based on operative knowledge practically learnt "*in situation*". Moreover, the driving task is performed by using an *artifact* (i.e. the vehicle), and the driving situation is directly *transformed* by the human operator's activity (e.g. car position on the road depending of the driver's action on the vehicle controls), as well as the situation *modifies* the driver's cognitive states (in terms of mental representation updating, for example, or new operative knowledge learning). Lastly, in accordance with the *ecological theory of Neisser* (1976), driver's perception in figure 2 is based on a dynamic *perceptive cycle* when (i) an active schema directs gathering-information activity (i.e. top down processes) and (ii) focus driver's attention on information currently available in the environment. Then (iii), this active schema provides a mental model that is continuously updated by dynamic integrating the new pieces of information collected into the road scene.

3. Computational and dynamic simulation of the driver's mental activities while driving

By considering this theoretical background, the COSMODRIVE model is composed of three main functional modules (i.e. the *Perception*, the *Cognition*, and the *Action* modules) in order to drive a virtual *Car* into a virtual *Environment* through two synchronized "Perception-Cognition-Action" regulation loops (Bellet et al., 2010): an attentional control mode (mainly focused on Rasmussen's rule-based behaviors, and simulated through *Driving Schemas*, and an automatic control loop (corresponding to the skill-based behaviors simulated through the *Envelope Zones* concept and the *Pure-Pursuit Point* method).

3.1 Modeling the explicit cognition: the *Driving Schemas*

Based on both the Piaget's concept of *operative scheme* and the Minsky (1975) *frames theory*, *driving schema* is a computational formalism defined in order to implement *operative driving knowledge* a the tactical level of COSMODRIVE (Bellet et al., 1999). They correspond to prototypical empirical situations, actions and events, learnt by the driver from practical experience.

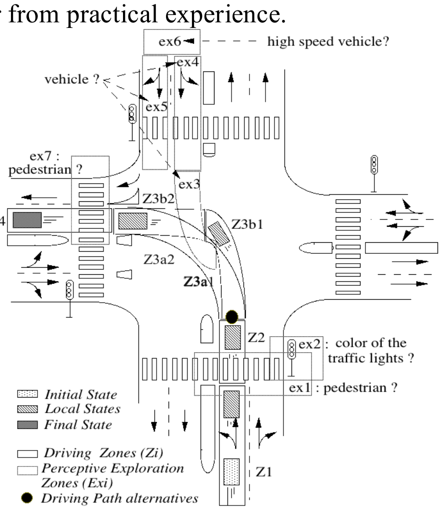

Figure 3: The *Driving Schemas* formalism

From a formal point of view (Figure 3), a *Driving Schema* is composed of (i) a functional model of road *Infrastructure*, (ii) a *Tactical Goal* (e.g. turn left), (iii) a sequence of *States* and (iv) a set of *Zones*. Two types of *Zone* are distinguished: *Driving Zones* (Z_i), corresponding to the driving path of the vehicle as it progresses through the crossroads, and the *Perceptive Exploration Zones* (ex_i), in which the driver seeks information (e.g. potential events liable to occur). Each driving zone is linked to *Actions* to be implemented (e.g. braking or accelerating, in view to reach a given state at the end of the zone), the *Conditions* of performing these actions, and the perceptive exploration zones that permit checking these conditions (e.g. color of traffic lights, presence of other road users). A *State* is defined by a vehicle position and speed. The different sequences of the driving zones make up the *Driving Paths* that progress from the initial to the final state (achievement of the tactical goal).

Once activated in working memory and instantiated with the road scene, the active driving schema becomes the *tactical mental representation* of the driver, which will be continually updated as and when s/he progresses into the current environment. Tactical representation corresponds to the driver's explicit awareness of the driving situation and provides a mental model of the road functionally structured, according to the tactical goal pursued by the driver in this particular context (e.g. turn on the left).

3.2 Modeling the implicit cognition: the *Envelope-Zones* and *Pure Pursuit Point* regulation strategies

At the operational level (corresponding to the automatic control loop presented in fig. 1), COSMODRIVE regulation strategy is based on two implicit regulation mechanisms: the *envelope zones* and the *pure pursuit point*. From a theoretical point of view (Bellet et al., 2007), the concept of envelope zones recalls two classical theories in psychology: the notion of *body image* proposed by Schilder (1950), and the theory of *proxemics* defined by Hall (1966), relating to the distance keeping in social interactions with other humans. Regarding car-driving activity, envelope zones also refer to the notion of safety margins. At this last level, COSMODRIVE model approach (Fig.4) is more particularly based on Kontaratos' work (1974), and distinguishes a *safety zone*, a *threat zone*, and a *danger zone* in which no other road user should enter (if this occurs, the driver automatically activates an emergency reaction).

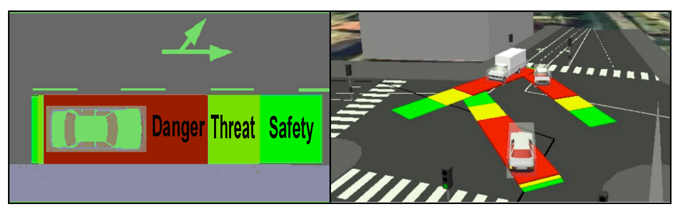

Figure 4: COSMODRIVE "Envelope-Zones" model

The envelope zones correspond to the portion of the path of driving schema to be occupied by the vehicle in the near future. Moreover, as an "hidden dimension" of the social cognition, as suggested by Hall's theory (1966), these proxemics zones are also mentally projected to other road users, and are then used to dynamically interact with them, as well as to anticipate and manage collision risks. This "virtual skin" is permanently active while driving, as an implicit awareness of our expected allocated space for moving. As with the Schilder's body schema, it belongs to a highly integrated cognitive level (i.e. implicit regulation loop), but at the same time favors the emergence of critical events in the driver's explicit awareness. Therefore, the envelope zones play a central role in the regulation of social as well as physical interactions with other road users under normal driving conditions (e .g. inter-vehicle distance keeping), and in the risk assessment of path conflicts and their management if a critical situation occurs (commitment of emergency reactions).

The second hidden dimension of the implicit cognition implemented at the operational level of COSMODRIVE is the *Pure Pursuit Point* method. This method was initially introduced for modeling in a simplified way the lateral and the longitudinal controls of an automatic car along a trajectory (Amidi, 1990), and has been adapted by Sukthankar (1997), and then Mayenobe (2004), for driver's situational awareness modeling. Mathematically, the pure-pursuit point is defined as the intersection of the desired vehicle path and a circle of radius centered at the vehicle's rear axle midpoint (assuming front wheel steer). Intuitively, this point describes the steering curvature that would bring the vehicle to the desired lateral offset after traveling a distance of approximately l. Thus the position of the pure-pursuit point maps directly onto a recommended steering curvature: $k = -2x/l$, where k is the curvature (reciprocal of steering radius), x is the relative lateral offset to the pure-pursuit point in vehicle coordinates, and l is a parameter known as the look-ahead distance. According to this definition, the operational control of the car by COSMODRIVE can be seen as process of permanently keeping the Pursuit Point in the driving path, to a given speed assigned with each segment of the current tactical schema, as instantiated in working memory.

4. The emerging living cognition

By using the functional architecture and the cognitive agents of COSMODRIVE described in figure 2, (ii) the *driving schemas* as operative knowledge activated and then dynamically updated in the form of a functional mental representation matched with the road scene, and (iii) the operational skills corresponding to the pure-pursuit point and the envelopes zones regulation process, it becomes thus possible to dynamically simulate of the driver's "living cognition". The central process that supports the living cognition is the *deployment* of the active driving schema, as instantiated in Working Memory through the current mental representation. This deployment consists in moving the car along a *driving path* (cf. fig. 3), by successively traveling through the different driving zones of the schema, from the initial state (i.e. Z1) until reaching the tactical goal (i.e. Z4). This deployment process may occurs at two levels: (i) at the representational level (*explicit* and *implicit* mental simulations of the future activity to be carried out), when the drivers anticipate and project themselves mentally in the future, (ii) and through the activity itself, during the effective implementation of the schema while driving the car. This twofold deployment is not performed by a specific process in COSMODRIVE. It is an *emergent* collective product, resulting from the combined effect of several cognitive processes (like *anticipation* or *decision-making*), and merged with the computations based on the *envelope zones* and the *pursuit point* regulation laws. As a result, the deployment process generates a particular *instance* of the active schema execution, composed of a temporal sequence of mental representations, causally interlinked, and corresponding to the driving situation as it is progressively understood and anticipated, then experienced, and lastly *acted* by the driver, along the driving path progression.

The figure 5 provides an example of COSMODRIVE simulation results, permitting to visualize the mental representation evolution of a novice driver (who has the intention to turn on the left), while approaching of an urban crossroads with traffic lights. In a first time (i.e. first left view, corresponding to the driver's mental representation at a distance of 30 meters of the traffic lights), the driver's situation awareness is centered on the near traffic and on the traffic lights color, that directly determine the short-term activity to be implemented. Then, as s/he progresses towards the crossroads, the driver's attention is gradually focused on the ahead area, and the traffic flow occurring in the intersection center is progressively integrated into the driver's mental representation (i.e. second left view, at a distance of 10 meters of the traffic lights).

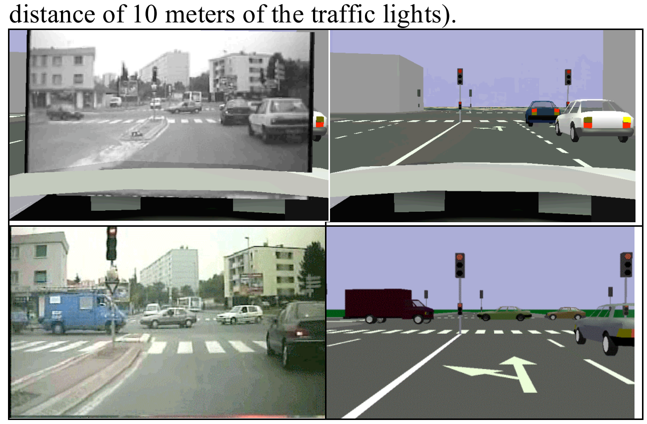

Figure 5: virtual simulation of a driver's mental models

The advantage of the driving schema formalism as defined in COSMODRIVE is to combine declarative and procedural knowledge in the unified computational structure. When associated with the operational regulation processes linked with the *envelope zones* and the *pursuit point* strategies, it is then possible to use such driving schemas as a structure of control for both monitoring the operative activity, as well as for supervising the mental derivation of the "schema deployment", as this process is implemented by the human cognitive system in order to anticipate future situational status, or to mentally explore the potential effects of an action before applied it. In accordance with the activity theories, these cognitive structures guarantee a continuum between the different levels of awareness (implicit *versus* explicit) and the activity control (tactical *versus* operational), thereby taking full account of the embedding of operative know-how (i.e. the level of implementation) in the explicit and decisional regulation loop of the activity.

5. Conclusion: "*in silico veritas*"

By considering the challenge of the *living cognition* study, it is needed to apprehend the dynamic functioning of the human cognitive system in interaction with the environment where s/he is currently immersed. Thus, computational models able to virtually simulate the human mental activities on computer are required. One of the key issues of the living cognition is mental representations simulation, that are dynamically elaborated and continually updated in the working memory of the human operator before (i.e. action planning) and during the activity, when practically carried out. Indeed, mental representations and operative activity are intimately connected. In the same way as the human activity fuels itself directly with mental representations, the operator's mental representations are also fuelled "by" the activity, and "for" the activity, according to a double deployment process: cognitive and representational, on the one hand, and sensorial-motor and executive, on the other.

The key mental structure supporting both drivers' mental representations and their activity are *driving schemas*. From a metaphorical standpoint, such schemas can be compared to a strand of DNA. They "genetically" contain all the potential behavioral alternatives that allow the driver to act within a generic class of situations. Nonetheless, only a tiny part of these "genotypic potentialities" will finally express themselves in the current situation – with respect to the constraints and specific characteristics of reality – during the cognitive (i.e. mental deployment), and then executive implementation of this schema (i.e. effective activity carried out to drive the car). And it is only through this dynamic process of deployment of operative mental representations, involving a collective effort of several cognitive processes, that certain of intrinsic properties of the *living cognition* will emerge. From this point of view, the scientific investigation of the living cognition cannot forego the use of computer simulation of the human mental activities, without taking the risk of being largely incomplete.

Acknowledgments

The research is currently supported by the European Commission Seventh Framework Program (FP7/2007-2013), in the frame of ISi-PADAS Project.

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