Time in consciousness, memory and human-robot interaction

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Abstract. Contemporary research endeavors aim at equipping autonomous robots with human-like cognitive skills, in an attempt to promote robotic intelligence and make artificial agents more natural and more human-friendly. However, despite the crucial role that sense of time has in our daily activities, the capacity of artificial agents to experience the flow of time remains largely unexplored. The inability of existing systems to perceive time acts as an obstacle in implementing conscious artificial agents that put their experiences on the past-present-future timeline and develop durable symbiotic relationships with humans. The present paper elaborates on time-cognition coupling suggesting that the equipment of artificial agents with human-like time perception and time processing capacities is a prerequisite for bringing robotic cognition close to human intelligence.

1 Introduction

Time perception is a fundamental component of cognition that structures the way we interpret procedures and events. As both perception and action evolve over time, timing is necessary to appreciate environmental contingencies, estimate relations between events and predict the effects of our actions. Since the day we are born, everyone's clock begins to run and our ability to perceive time links what we are to the past and the future, to our experiences and prospects.

Despite the fundamental role of time in human cognition it remains largely unexplored in the field of robotics. Surprisingly, there are not yet robotic systems equipped with temporal cognition, that is, which are aware of the notion of time as a unique entity that can be processed on its own right. Early works such as considering the integration of sensory-motor information over time [1], or turn taking [2], have not focused on sense of time and how artificial agents will acknowledge time as separate dimension of the world. A more explicit focus on the notion of time has self-organized in robotic agents solving a two-rule switching task, where duration is used to drive agent's decision in following either the one rule or the other [3, 4]. In the last years we have developed a strong interest on temporal cognition investigating possible time representations and duration processing mechanisms by considering some of the most widely used tasks by interval timing community, namely duration reproduction and duration comparison [5, 6].

The current paper aims to present at the interdisciplinary audience of the SAB conference the key role of time perception in steering and improving the adaptivity of biological and artificial systems. More specifically, our intention is to make explicit that an animal or animat may exploit temporal information (e.g. how much time is required to accomplish a task) to better adapt its strategy towards a long-term goal. At the same time, considering the short-term aspects of life, time perception is necessary to make a system feel rush and accordingly adapt to emergency situations.

The present review elaborates on mind-time interactions, considering particularly the role of time in (i) developing consciousness and the sense of self, (ii) encoding, managing and processing past and future events, (iii) enhancing fluency in human-robot interaction. Additionally we discuss recent neurophysiological findings on time perception and we outline computational models addressing the interaction of time perception with other cognitive modalities, providing hints on equipping artificial agents with temporal cognition.

2 Time and Consciousness

Time perception is directly linked to consciousness because it makes us aware of change, movement, and succession across brief temporal intervals. By remaining conscious in the long-term we are able to experience the temporal framework and the evolution of events in the world. Sense of time supply us with access to our own past structuring our personality and the notion of self.

Traditional explanations on how the sense of self links to time perception make a division between the Moving-Time and Moving-Ego metaphors [7]. In the former, “time events” move with respect to a fixed observer from front (future) to back (past) (e.g. the winter went by), while in the latter the “observer” moves forward on the past-present-future timeline (e.g we are approaching the end of the year). In both cases there is a uni-directional flow of time relative to the observer. Directionality is a critical property that differentiates time from other senses (i.e. we can never experience a moment twice, but we can hear the very same tone as many time we want) suggesting that cognitive models should not consider time as one more typical system parameter.

According to Damasio, there are three levels of consciousness, namely protoself, core consciousness and extended consciousness [8]. Humans are assigned to the higher level, which assumes that the sense of self exceeds bodily states and is linked to historical times, enabling present to be associated with the past and the future. Animals are typically assigned to lower levels of consciousness, because they live their life being largely stuck in the present moment (i.e. be aware of only a short permanent present). In contrast, humans see the world from numerous time perspectives. It is our ability to travel backward and forward in subjective time, to recall or imagine events, that enables strong personal awareness [9]. Therefore time perception makes the difference.

By making artificial agents aware of and sensitive to the passage of time, we pave the way for enabling robots to recall/predict events and properly adapt to the heavily time structured human social life.

3 Time in Knowledge and Memory

Time plays a key role in the encoding of human memories and thus it is very surprising that, so far, knowledge has been encoded in artificial systems using flat, time-less representations that consider what and where, but not when. Even state of the art robots are not aware of the ordering of their experiences and cannot understand that what they perceive now might have been in a different state in the past. Only recently the EU funded project STRANDS has promised to initiate the 4D rather than 3D mapping of the world.

For humans, the ability to travel in the past is a highly integrative and constructive procedure that is based on the incremental synthesis of past events [10]. Interestingly, almost the same neural mechanisms are also employed when we try to predict future [11]. This suggests that robotic cognition may gain significantly by acquiring a mental time travel capacity that could subsequently support many other cognitive skills (mind reading, causal inferencing, etc.).

To accumulate knowledge over time, learning algorithms describe sequential changes in memory, triggered by the appearance of certain stimulus [12]. Temporal properties play a key role in improving the ability of artificial agents to encode new knowledge and be able to recall it based on either temporal (which city hosted SAB 2008?) or spatial (when SAB was in Osaka, Japan?) criteria.

In the opposite direction, our ability to forget over time enables the reorganization and better management of knowledge. The typical explanation of forgetting assumes information to decay over time making information held in short-term memory to be quickly forgotten unless it is constantly rehearsed or refreshed [13]. This is an issue that has recently attracted research interest in the field of robotics, with experimental works showing that robotic performance may significantly improve by means of forgetting unnecessary, erroneous, and expired data [14, 15].

Given that knowledge sets the framework in which robots perceive, understand and act in the world, by considering the temporal aspects of knowledge and memories robots, will be capable to exploit the past in order to decide how to achieve certain goals in the future.

4 Symbiotic Human Robot Interaction

The core idea behind symbiotic human-robot interaction (HRI) regards the close and long-term coupling between humans and artificial agents. However, the majority of existing works assume interaction to evolve isolated from the ongoing and long lasting real world procedures. In order to develop robots that are actively integrated into the time-structured human life, artificial agents must be equipped with time processing skills, being capable to link their actions to the past and the future of the world. Broadly speaking, we can identify two dimensions in which time affects human-robot interaction.

- in dialogue management, where turn taking, action synchronization, and other short-term issues of multi-agent interaction are processed,
- in collaborative information processing, where the accumulated experiences of human-robot interaction lead to gradually more productive synergies between the two sides.

While an adequate number of works has explored the first dimension of human-robot interaction [16, 17], the latter remains largely unexplored.

To highlight the role of time in synergetic HRI, we may consider a robotic assistant that helps its owner to prepare a dinner. The robot must recall past dinners with the participation of the visitors, bringing on its mind the type of wine they are fun of. To successfully recall the past, the robot is necessary to shift attention not in space (as usual) but in time, being able to recall information from a specific past period. The information gathered must be projected to the present, therefore affecting important aspects of the dinner preparation. The human mind is particularly efficient in jumping back and forth from one time period to the other, and our ability to perceive the interdependencies of asynchronous events enables their integration into a meaningful story that unfolds over time. Such a capacity is also crucial for artificial agents. By shifting attention to the past, the agent accomplishes time-based or context-based memory search, and by shifting attention to the future, the agent accomplishes action planning, targeting specific goals at specific moments in time.

Sense of time is also important for the here and now aspects of the interaction. Even if during an interaction session robot's attention may be focused on a past time period, a part of its mind must remain situated to the present dealing with real-time environment interaction issues. For example, time pressure significantly affects the way we choose and express actions. Therefore, in an emergency situation (e.g., barbecue meat is almost burned) the robot must not go for the more smooth or energy efficient solution, but for the faster solution.

Naturalistic multi-agent interaction involves a broad set of skills (e.g. perception, attention, memory storage and recall, future prediction, planning) with a strong temporal dimension that, if considered in computational implementations, has the potential to significantly improve human-robot synergies.

5 Time perception mechanisms in the brain

Understanding the time processing mechanisms in the brain of animals and humans is a timely and very challenging issue that has attracted rapidly increasing interest in the neuroscience and cognitive science communities. Contemporary review papers and special journal issues have summarized and are testament to the new and burgeoning scientific findings in the field [18–21].

Over the past decade, a number of different brain areas have been implicated as key parts of a neural time-keeping mechanism, notably (among many others), event timing in the cerebellum [22], generalized magnitude processing for time, space and number in the right posterior parietal cortex [23, 24], working memory related integration in the right prefrontal cortex [25, 26], a right fronto-parietal network [27], coincidence detection mechanisms using oscillatory signals in fronto-striatal circuits [28], hippocampal time-cells focused on the relation of time and distance [29], as well as integration of ascending interoceptive (that is, body) signals in the insular cortex [30, 31]. The participation of many brain areas in the processing of temporal information attest the key role of time in a broad range of cognitive capacities.

6 Computational models of time perception

The following paragraphs summarize existing computational models dealing with the sense of time. The first part considers models of time perception that operate largely isolated from other cognitive skills, while the second addresses cognitive skills that have been extended in a temporal dimension.

Time/Duration Perception. In an attempt to explain where and how time is processed in the brain, a large number of neurocomputational models have been implemented, most of them concentrating on duration perception. Broadly speaking, two main approaches have been proposed in the literature to describe how our brain represents time [32, 33]. The first is the dedicated approach (also known as extrinsic, or centralized) that assumes an explicit metric of time. The models included in this category employ mechanisms that are designed specifically to represent duration. Traditionally such models follow an information processing perspective in which pulses that are emitted regularly by a pacemaker are temporally stored in an accumulator, similar to a clock [34–36]. This has inspired the subsequent pacemaker approach that uses oscillations to represent clock ticks [37, 38]. Other dedicated models assume monotonous increasing or decreasing processes to encode elapsed time [39, 40]. The second approach includes intrinsic explanations (also known as distributed) that describe time as a general and inherent property of neural dynamics [41–43]. According to this approach, time is intrinsically encoded in the activity of general purpose networks of neurons. Therefore, rather than using a time-dedicated neural circuit, time coexists with the representation and processing of other external stimuli. However, besides the key assumption of multi-modal neural activity, the existing computational implementations of intrinsic interval timing models are not yet coupled with other cognitive or behavioral capacities within a broader functional context, and in that sense, the internal clock remains unaffected by outside processes. Only the Behavioral Theory of Timing [44] and the Learning to Time [45] make explicit coupling between time perception and behavior, assuming that the behavioral vocabulary of subjects and their current behavioral state support duration perception.

An attempt to combine dedicated and intrinsic approaches is provided by the Striatal Beat Frequency (SBF) model which assumes that timing is based on the coincidental activation of basal ganglia neurons by cortical neural oscillators [46, 47]. The SBF model assumes a dedicated timing mechanism in the basal ganglia that is based on monitoring distributed neural activity in the cortex. Recently, SBF has been integrated into a generalized model of temporal cognition that subserves different aspects of perceptual timing, either duration based or beat-based [48]. In the same line, our recent work with simulated robotic agents has suggested a new biologically plausible mechanism for duration processing that incorporates both dedicated and intrinsic characteristics [49].

Cognitive Models Exploiting Sense of Time. Recently, an increasing number of computational cognitive models aim at integrating sense of time. The following list provides an outline of the existing approaches which accomplish early steps towards integrating time perception in intelligent artificial systems research:

- Time in decision making [3]. Artificial agents self-organize time perception capacity to support decision making.
- A grounded temporal lexicon [50]. Lingodroids (language learning robots) are employed to learn terms linking space and time.
- Interval timing grounded in motor activity [51]. Explore how body and arm movement serve as a rough temporal yardstick for time perception.
- Representation of duration [6]. Multimodal duration processing by artificial agents.
- Time perception as a secondary task [52]. Explore the coupling of interval timing, attention, perception and learning in the accomplishment of dual tasks.
- Past, Future Perception [53]. Predictable internal state dynamics result in significantly more robust systems, compared to equally performing memory-less systems which develop much more fragile internal mechanisms.
- Mental Time Travel [54]. Explore the ability to recall and potentially re-experience a previously experienced motion trajectory, by associating specific stimuli with specific memories.
- Learning Through Time [12]. Explore the temporal properties of learning by considering how the memory representation of stimulus changes over time.
- Forgetting [13]. Explaining how working memory evolves and reshapes through time.
- Memory Reconsolidation [55]. Episodic encoding based on the binding of events to their temporal context and learning-based memory reinstantiation.

As discussed above, time plays a key role in consciousness, memory and human-robot interaction. The integration of the above mentioned temporally extended cognitive capacities into a fully entimed system will pave the way for the next generation of robotic systems that will be actively integrated into human daily activities.

7 Implementing Temporal Cognition in Robotic Systems

The integration of the cognitive models summarized above is certainly not a straight forward procedure, given the heterogeneous computational approaches and the diverse assumptions adopted. However, there are directly applicable approaches that rely on conventional artificial intelligence methods e.g., temporal logic, or event calculus [56, 57] that can significantly facilitate accomplishing time processing in robotic systems. It is surprising that despite the extensive experience that exists with such systems, the latter are rarely employed in robot implementations. However, it is noted that the use of time-stamps or other clock measures do not guarantee temporal cognition for artificial agents [58]. In fact, humans develop temporal cognition before being capable to use clocks, while animals that also perceive and process time cannot of course use clocks at all! Similar to robot vision, grabbing an image of RGB pixels, does not mean that thesystem is able to see and understand the world.

A crucial decision towards implementing artificial temporal cognition regards how time will be represented in the artificial mind. For example time-stamping and storing events in the level of milliseconds, implies that the robot will be aware of every single moment of its past (e.g. 6-months ago). Such an approach would render looking back in time computationally infeasible for artificial systems. Following a more biologically plausible approach, the perception of the past-present-future timeline assumes finer temporal granularity close to the present and a gradually coarser granularity when traveling backward and forward in time. This is the approachthat we follow in our ongoing work.

Overall, to proceed effectively towards equipping artificial agents with the ability to perceive and process time, we may consider the natural, developmental procedure of the human brain that enables time processing capacities to develop and gradually integrate with other cognitive skills. While primary sense of time matures very early in the human developmental procedure, our temporal cognition continuously improve until adolescence [59, 60]. Following a similar procedure, computational implementations should first focus on basic skills such as duration processing or synchrony, then consider the wider timeline that spans over past present and future to explore time in memory, attention, learning, and action planning, proceed with time language interactions and finally consider how time integrates into complex cognitive capacities such as mind reading, or imagination.

8 Conclusions

Sense of time is without doubt not an optional extra but a necessity towards the development of truly autonomous and intelligent machines that are seamlessly and actively integrated into human societies. Evidently, if we are going to ever implement intelligent robots that live next to us and operate in a way comparable to humans, then these robots will be definitely equipped with advanced time perception and processing capacities. Systematic research efforts enabling artificial agents to consider the heavily time-structured human life are expected to provide new impetus in the way we study and implement intelligent systems, closing the gap between human and artificial cognition.

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