frontiers in
NEUROROBOTICS

PERSPECTIVE ARTICLE
published: 19 September 2011
doi: 10.3389/fnbot.2011.00002

Temporal cognition: a key ingredient of intelligent systems

Michail Maniadakis* and Panos Trahanias

Computational Vision and Robotics Laboratory, Institute of Computer Science, Foundation for Research and Technology Hellas, Heraklion, Crete, Greece

Edited by:
Sandro Mussa-Ivaldi, Northwestern University/Rehabilitation Institute of Chicago, USA

Reviewed by:
Amir Karniel, Ben Gurion University, Israel
Stefano Nolfi, Consiglio Nazionale delle Ricerche, Italy
Marc Wittmann, Institute for Frontier Areas of Psychology and Mental Health, Germany

****Correspondence:***
Michail Maniadakis, Computational Vision and Robotics Laboratory, Institute of Computer Science, Foundation for Research and Technology Hellas, N. Plastira 100, Vassilika Vouton, Heraklion, Crete, Greece.
e-mail: mmaniada@ics.forth.gr

Experiencing the flow of time is an important capacity of biological systems that is involved in many ways in the daily activities of humans and animals. However, in the field of robotics, the key role of time in cognition is not adequately considered in contemporary research, with artificial agents focusing mainly on the spatial extent of sensory information, almost always neglecting its temporal dimension. This fact significantly obstructs the development of high-level robotic cognitive skills, as well as the autonomous and seamless operation of artificial agents in human environments. Taking inspiration from biological cognition, the present work puts forward time perception as a vital capacity of artificial intelligent systems and contemplates the research path for incorporating temporal cognition in the repertoire of robotic skills.

Keywords: sense of time, time processing, time perception, brain-inspired cognition, robotic systems

INTRODUCTION

For humans and animals, sensing and knowing the world arises through spatio-temporal experiences and interpretations. This means that not only spatial information but also time has a crucial role in cognition. Especially for humans, the capacity to experience and process time is fundamental for many of our daily activities, such as recalling our experiences or making and executing plans to accomplish certain goals. From a social perspective, time is important for monitoring and predicting the behavior of others, sharing goals and plans with friends, communicating using tenses in natural language, etc. All the above are testaments to the argument that time is essential for almost every activity we engage in.

Alas, despite the fundamental role of time in natural cognition, current endeavors in the development of robotic intelligence are by no means directed toward encompassing time processing in the systems' repertoire of capacities. This is really surprising given the extensive inspiration that robotic community has taken from the cognitive modalities of the brain during the last decade.

In the current article we use temporal cognition (TC) as an umbrella term describing the set of cognitive functions that support the broad range of our time experiences. Formally speaking, we define TC as follows:

Definition: *Temporal Cognition encompasses the set of brain functions that enable experiencing the flow of time and processing the temporal characteristics of real world phenomena, accomplishing (i) the perception of synchrony and ordering of events, (ii) the formation of the experienced present, (iii) the perception of different temporal granularities, (iv) the conceptual abstraction and processing of durations, (v) the mental traveling in future and past time, (vi) the social sharing of temporal views about the world.*

The cognitive mechanisms that are currently implemented in robotic systems focus mainly on the spatial aspects of the world, resulting in artificial agents which are "stuck in time" (a phrase borrowed from Roberts, 2002). Existing robots operate very much in the "now" of our world, with no concept of a time dimension that extends into past and future. Note that being capable to experience and process time is drastically different to what is now known as the dynamic cognition approach (van Gelder, 1998; Beer, 2000). The latter highlights the spatio-temporal character of perception and action, considering brain as a dynamical system that is strongly linked with the body and the continuously changing environment. Previous works have examined tasks with clear temporal characteristics, such as the integration of information over time, to deal with sensory aliasing (Nolfi and Marocco, 2001), and turn-taking alternation to coordinate the behavior of two agents (Iizuka and Ikegami, 2004). Despite considering the coupled spatio-temporal nature of real world phenomena, the dynamic cognition approach has not provided robots with any kind of "sense of time" that may operate in isolation from space. This lack of "time sense" may still not be an issue when considering simple behavioral tasks; for example, recent works (Conditt and Mussa-Ivaldi, 1999; Karniel and Mussa-Ivaldi, 2003) have considered human motion adaptation and have been unable to identify clear temporal parameters. However, there are many aspects of our life which assume processing the uniquely identified time concept, e.g., when we estimate how much time is left to finish exams writing, or when we direct our attention to a particular time period in the past. In other words, humans exhibit a time-dedicated cognitive capacity that operates decoupled from space and it is hard to be implemented within the ordinary dynamic cognition framework, e.g., measure elapsed time and perform numerical duration calculations. To develop such skills, cognitive systems (without excluding dynamical system implementations) need to follow specialized architectures that allow time to be experienced, abstracted, and processed, providing added value to the existing cognitive capacities of artificial agents.

Without sense of time and TC, the ability of robots to understand the causal temporal linking of processes and events is severely limited. This in turn implies that they cannot sufficiently learn from past experiences, they cannot anticipate the future, they cannot plan successfully their activities in the long and short term, and other shortcomings. Interestingly, the distinction between past, present, and future, and its important role in cognition, has been partially discussed in previous studies (Varela, 1999; Tani, 2004) without however considering the full extent of TC aspects. The current paper aims to reveal the lack of TC in artificial cognitive systems, to discuss the fundamental role of TC in developing intelligent and social behaviors, to direct research attention on equipping artificial cognitive systems with TC capacity, as well as to contribute methodological cues with the potential to facilitate artificial TC implementation.

TEMPORAL COGNITION BRAIN MECHANISMS

The different aspects of TC listed in the above definition develop gradually in humans starting from the late infancy (at about the age of 12 months) when primitive ability to experience the flow of time is obtained (Arterbery, 1993), continue during childhood implementing the ability to think of future at about the age of 4 (Atance and Jackson, 2009), and become fully mature to adult-like levels by the age of 12 (Droit-Volet et al., 2006).

The investigation of the brain mechanisms involved in the perception and processing of time has attracted significant research interest in brain science during the last decade. Contemporary review papers and special journal issues have summarized the new and burgeoning scientific findings in the field (Allan and Church, 2002; Szelag and Wittmann, 2004; Meck, 2005; Crystal, 2007; Ivry and Schlerf, 2008; Tarlaci, 2009; Wittmann and van Wassenhove, 2009). It is now well established that, despite the fundamental role of time in our life, there is no region in our brain that is solely devoted to the sense of time (this contrasts to the exclusive representation of audition, vision, touch, proprioception, taste, and other senses in specific cortical regions). However, over the past decade, a number of different brain areas have been implicated to contribute in time-experiencing including (among others), the cerebellum, right posterior parietal cortex, right prefrontal cortex, fronto-striatal circuits, and insular cortex for duration perception (Lewis and Miall, 2003; Hinton and Meck, 2004; Bueti et al., 2008; Ivry and Schlerf, 2008; Wittmann, 2009), the inferior frontal and superior temporal lobes, hippocampus, medial prefrontal, medial parietal and posterior cingulated cortex for past–future distinction, and mental time travel (Botzung et al., 2008; Suddendorf et al., 2009; Viard et al., 2011), the prefrontal, inferior parietal cortex, superior colliculus and insular cortex for synchronous, and asynchronous event distinction (Dhamala et al., 2007; Kavounoudias et al., 2008), the posterior sylvian regions, posterior parietal, and temporo-parietal networks for temporal order judgment (Woo et al., 2009; Bernasconi et al., 2010; Kimura et al., 2010). The involvement of many brain areas in TC is explained by the significant contribution of multiple cognitive processes such as attention, working-memory, decision making, emotions, etc., in experiencing and processing time (Livesey et al., 2007). Therefore, slight perturbations on these processes may affect our time experiences, explaining why subjective time (how each one of us is perceiving the flow of time) is in principle different than the objective, physical time (Searle, 1992).

The aforementioned highly distributed network of brain areas that supports TC suggests that the sense of time relies on, and possibly emerges from, multi-modal cortical interactions. In-line with this, it has been recently suggested that time perception plays an important role in the fusion of perceptuo-motor information throughout the cortex, and the accomplishment of complex cognitive tasks (van Wassenhove, 2009). This is because TC implements a framework that enables associating asynchronous events (e.g., the light blue color of the ball that is now located in front of me, brings into my mind the blue of the sea I used to swim last summer). In that way, TC supports making sophisticated thoughts that may span in a wide period of time, paving the way for high-level cognition. Overall, time plays an important role in binding our experiences, mental states, goals, and behaviors, significantly supporting our daily activities.

TEMPORAL COGNITION IN ROBOTIC SYSTEMS

In the field of robotics, intelligence has traditionally aimed at exploiting the information provided by specialized sensory devices, being appropriately processed to select the next possible action. This widely used scheme has enabled robots to effectively accomplish tasks for specific application domains. The additional integration of brain-inspired mental processes, such as attention, association, learning, communication, etc., in artificial cognitive systems, has further improved robotic capacities in accomplishing complex tasks as well as in switching from solitary to social behavior. Besides these important advancements, existing artificial agents are still unable to consider many of the temporal properties accompanying our world, constraining their involvement into real life.

In order to achieve natural human-like performance, robotic systems need to incorporate the fundamental cognitive skills of biological agents. It is now known that apart from humans, many animals such as monkeys (Medina et al., 2005), rats (Guilhardi et al., 2005), and even zebra-fish (Sumbre et al., 2008), are capable of processing time. Therefore, it seems likely that TC is a prerequisite for intelligent behavior. Unfortunately, this capacity is lacking from robotic systems, which almost always neglect the temporal extent of real world phenomena. The current paper puts forward TC as a vital capacity of intelligent systems. More specifically, we argue that the equipment of robots with TC is a critical milestone for accomplishing robotic intelligence, having the potential to provide new impetus in implementing artificial agents operating autonomously in human environments. In practical terms, we can identify at least three dimensions in which TC can improve robotic cognition.

- *Advance internal cognitive processes*: There are many mechanisms with an important role in shaping cognitive dynamics, such as learning, memorization, forgetting, attention, association, and others, that can significantly benefit by considering temporal information. For example, new learning algorithms may be implemented that consider the details of past events when adjusting decision making procedures, time-based association mechanisms may be used to enable future conflict prediction, while directing attention on a particular time period in the past will enable considering relations between a specific set of events.

- *Develop skills dealing with the manipulation of time*: Artificial TC will provide robotic agents with the capacity to process all different aspects that time is involved in our daily life, accomplishing tasks which are currently out of their scope. For example, robots may be capable of (i) synchronizing with natural human actions (currently humans are mainly synchronized to robots); (ii) abstracting and categorizing the time scales required for the evolution of different processes; (iii) being aware of the temporal order of their own experiences; (iv) considering the causal relationship linking the present and future with past events that may have occurred many hours or days ago, and others.
- *Develop skills that implicitly involve time processing*: Time is an important parameter for many low and high-level skills. This is because even simple actions (e.g., object grasping) include a critical "when" component (Battelli et al., 2008) that links a given behavior with the ongoing real world processes. Moreover, high-level cognition that is typically less related with the here and now of the world, requires the association and reasoning on events that occurred, or will occur at different times (e.g., mind reading links past knowledge with future actions). Therefore, both low and high-level cognitive skills can gain significant efficiency through artificial TC.

Overall, enabling robots to experience and process time will support a broad set of cognitive functions, rendering the operation of artificial agents more natural and will thus facilitate the active and seamless involvement of robots in human everyday activities.

CHALLENGING TC CAPACITIES FOR ROBOTIC TECHNOLOGY

The fact that robotic systems are already equipped with clocks occasionally makes people believe that TC can straightforwardly be implemented, rendering time perception, and processing an exception to the well known "no free lunch" theorem (Wolpert and Macready, 1997). Evidently, this is far from reality, in the same way that getting spatial information was far from achieving efficient robotic navigation in human environments (it took more than a decade of intense research to implement robust navigation methodologies). In other words, getting a bunch of measurements from a robot's clock is far from efficiently incorporating time in the cognitive loop of artificial agents.

As an example case, let us consider a robot that operates as assistant for people in home environments. The robot helps with cleaning the house and when it is close to finishing the job, the person controlling the robot requests: "Since you are almost done with dusting the furniture let's have now a chess game." Obviously, in the current context, *now* means in the next few minutes (i.e., it is in fact the future that is referred as present). The robot has to first finish with cleaning and then setup the chess game. During chess playing the person may come up and say: "I really feel bad with my stomach-ache; I need my medicine now." This time, the robot has to understand that *now* corresponds to an urgent situation, stop playing chess and bring medicine as soon as possible. At the end of the day, the person is ready to go to bed, saying "the alarm system is installed in the house, now you should observe the indicator light to make sure that access to our house is not violated." Noticeably, in the latter case *now* means for the whole night period and actually for every night from now on. Clearly, humans have a very flexible way of considering present that depends on the context of a given task, and it is currently particularly difficult to develop a similar capacity for artificial agents. Note that the definition of present affects also other important aspects of TC such as past–present–future distinction or synchrony (i.e., it is different to synchronize in a 10-min cooking task, than synchronizing in a 2-year book writing task).

Although time may often be bypassed when we consider accomplishing short specific tasks (an issue that has dominated robotic research during the last decades), this is not true for complex natural scenarios where time is greatly involved in everyday life. Therefore if we are going to ever implement intelligent robots seamlessly interacting with humans, such robots will be equipped with advanced, human-like TC.

IMPLEMENTING ARTIFICIAL TEMPORAL COGNITION

Addressing artificial TC for robotic systems is a most challenging research endeavor. This is partly due to the fact that the capacity to experience and process time has to be seamlessly and effectively integrated with the already implemented robotic skills. Undoubtedly, the latter is affected by the computational approach adopted for implementing TC, which is critical for maximizing the benefits that cognitive systems will gain from this new computational modality. Broadly speaking we can identify two main approaches for equipping robots with TC.

The first approach relies on artificial intelligence (AI) methods that accomplish time-dedicated processing, e.g., temporal logic, or event calculus (Brandano, 2001; Fisher et al., 2005). It is surprising that despite the extensive experience that exists with such systems, the latter are rarely employed in robot implementations. This fact also highlights a main argument of the current paper, that the robotics community has not adequately appreciated the fundamental role of time in cognition and therefore it is now high time to make a shift toward artificial TC. The AI approaches mentioned above treat time as an isolated piece of information that can be directly obtained by computer clocks for labeling events and subsequently processed through dedicated mathematical procedures. A significant advantage for the underlying approach is the extensive know-how already obtained, which can be readily employed to facilitate the processing of time. However, such an AI approach typically results in compact implementations, meaning that TC will operate as a rather separate module of the overall cognitive system, being minimally affected by other cognitive processes. Clearly, such a module for experiencing, representing and processing time can hardly parallelize with the known TC brain processes where there is no time-dedicated region and time-experiencing emerges from the interaction of sensory, motor, cognitive, and emotional modalities (Wittmann and van Wassenhove, 2009). Moreover, the use of clocks, is only one aspect of time processing that does not guarantee TC capacity (in fact, humans develop TC before being capable to use clocks, while animals that also perceive and process time cannot of course use clocks at all!). In a broader sense, we note here that the "good old fashioned AI" approaches have been criticized in many ways by the robotics community (Wilson, 2002; Steels, 2003). It is now widely accepted that temporal and other logics can deal with only a limited set of real world circumstances (Pfeifer and Scheier, 1999), and it seems unlikely that they can support the development of near-natural intelligence in artificial systems.

The second alternative approach aims at the computational replication of the TC working principles of the human brain. Such an approach assumes collaboration between robotic and brain science communities to abstract the neural mechanisms accomplishing TC and implement their computational counterparts in artificial cognitive systems. Evidently, the brain-inspired approach has high potential to result into artificial cognitive systems equipped with human competent TC. At the same time, due to the complexity and the highly distributed nature of biological TC mechanisms, this approach fosters the revealing of the brain working principles. Extensive testing of the implemented models may facilitate the *in silico* investigation of TC processes, providing valuable feedback to brain science regarding time processing functions and their role in cognition (e.g., by offering a valid computational test-bed where alternative theories may be evaluated). In other words, the bio-inspired approach places neuroscientific and computational research efforts in a closed loop where new findings in one of them will provide input for the advancement of the other, reinforcing continuous improvements in the two fields.

To simulate the highly distributed network of brain areas supporting TC (see above), computational modules having both temporal and other cognitive functional responsibilities need to be implemented. The connectivity of such modules will base on transfer components that monitor, extract and forward either temporal or other ordinary cognitive information. This approach is in agreement with the modern view on time-experiencing, asserting that time may be sufficiently encoded on neural state dynamics and can be extracted through appropriate monitoring processes (Karmarkar and Buonomano, 2007). Moreover, this is in-line with (van Wassenhove, 2009), suggesting that the monitoring of brain processes without conscious perception of time may lead, at a second stage, to time flow experiencing. The implementation of a large scale brain-inspired system will exploit the interaction between cognitive modalities accomplishing the fusion of sensory information and the association of different knowledge items, therefore providing added value to the already implemented perceptual, motor, cognitive, and emotional robotic capacities. Interestingly, due to the crucial role of time in many high-level and social cognitive skills, such as cause attribution, prospective memory, executive control, mind reading, multi-agent planning, and others, the equipment of artificial systems with TC will enable the aforementioned skills to subsequently develop in robotic agents.

The majority of existing computational models dedicated to time processing focus on the duration estimation aspect of TC (Matell and Meck, 2004; Zakay and Block, 2004; Machado and Arantes, 2006; Arantes, 2008). Additional models have been recently implemented to address mental time travel into the past (Hasselmo, 2009; Polyn et al., 2009; Hasselmo et al., 2010), without however considering future time traveling. All models mentioned above operate in a pure theoretical level without being assessed in real world contexts. The robotic instantiation of these models will place time-experiencing within the framework of embodied cognition, facilitating their real world assessment. The idea of embodiment is in accordance with modern theories considering time perception as the integration of ascending interoceptive (i.e., body) signals (Craig, 2009; Wittmann, 2009).

Our recent works have investigated the role of environmental temporal constraints in shaping cognitive mechanisms (Maniadakis et al., 2009a,b). It has been shown that system dynamics tend to self-organize mechanisms that consider and exploit time, in order to support the development of high-level cognitive skills (in particular, executive control, in the studies pursued). Interestingly, our more recent study on a similar topic (Maniadakis et al., 2011), has provided a new suggestion on the widely studied question addressing the existence or not of separate systems for perceiving intervals of different temporal granularities (Lewis and Miall, 2003; Wittmann and van Wassenhove, 2009). The alternative explanation that has been inspired by the autonomously self-organized model in our simulations, suggests that principal components of the same overall system may account for processing each granularity. This means that the underlying subsystems are only partially distinct, requiring each other in order to operate properly. Still, the primitive time perception skills implemented in our works can hardly compare to the natural duration processing capacity, and they are clearly far below the full extent of human and animal TC. Our ongoing work is currently focusing on the exploration of duration representation and duration comparison mechanisms in order to contribute one more piece in the puzzle of artificial TC implementation. The latter is suggested as a major robotics research goal, that is expected to substantially contribute to the advent of intelligent robots.

CONCLUSION

The current paper focuses on the ability of robotic agents to experience and process the flow of time. Surprisingly, robots have perfect time sensors (i.e., computer clocks) but poor TC capacity, while humans that have no time sensory system and measure time very inaccurately develop very efficient TC capacity. As it is argued throughout the paper, artificial cognition is currently not modulated by temporal features as humans experience them and this fact greatly obstructs robotic agents in developing sophisticated cognitive skills. In order to provide new impetus in robotic cognitive systems, it is now high time to direct research efforts on the exploration of robotic time perception and processing abilities. This will be a significant milestone in bridging the gap between human and artificial cognition. The equipment of robots with the ability to consider the temporal dimension of real world phenomena has the potential to enable robots to be seamlessly and actively integrated into human environments.

REFERENCES

Allan, L. G., and Church, R. M. (2002). Special issue honouring the career of professor John Gibbon. *Learn. Motiv.* 33. doi: 10.1006/lmot.2001.1114

Arantes, J. (2008). Comparison of scalar expectancy theory (SET) and the learning-to-time (LeT) model in a successive temporal bisection task. *Behav. Process.* 78, 269–278.

Arterbery, M. (1993). Development of spatiotemporal integration in infancy. *Infant Behav. Dev.* 16, 343–363.

Atance, C. M., and Jackson, L. K. (2009). The development and coherence of future-oriented behaviours during the preschool years. *J. Exp. Child Psychol.* 102, 379–391.

Battelli, L., Walsh, V., Pascual-Leone, A., and Cavanagh, P. (2008). The "when" pathway explored by lesion studies. *Curr. Opin. Neurobiol.* 18, 120–126.

Beer, R. (2000). Dynamical approaches to cognitive science. *Trends Cogn. Sci.* 4, 91–99.

Bernasconi, F., Grivel, J., Murray, M., and Spierer, L. (2010). Interhemispheric coupling between the posterior sylvian regions impacts successful auditory temporal order judgment. *Neuropsychologia* 48, 2579–2585.

Botzung, A., Denkova, E., and Manning, L. (2008). Experiencing past and future personal events: functional neuroimaging evidence on the neural bases of mental time travel. *Brain Cogn.* 66, 201–212.

Brandano, S. (2001). "The event calculus assessed," in *Eighth International Symposium on Temporal Representation and Reasoning, TIME 2001*, Civdale del Friuli, 7–12.

Bueti, D., Bahrami, B., and Walsh, V. (2008). The sensory and association cortex in time perception. *J. Cogn. Neurosci.* 20, 1054–1062.

Conditt, M. A., and Mussa-Ivaldi, F. A. (1999). Central representation of time during motor learning. *Proc. Natl. Acad. Sci. U.S.A.* 96, 11625–11630.

Craig, A. D. (2009). Emotional moments across time: a possible neural basis for time perception in the anterior insula. *Philos. Trans. R. Soc. B*, 364, 1933–1942.

Crystal, J. (2007). The psychology of time: a tribute to the contributions of Russell M. *Church Behav. Process.* 74.

Dhamala, M., Assisi, C., Jirsa, V., Steinberg, F., and Kelso, S. (2007). Multisensory integration for timing engages different brain networks. *Neuroimage* 34, 764–773.

Droit-Volet, S., Delgado, M., and Rattat, A. C. (2006). "The development of the ability to judge time in children," in *Focus on Child Psychology Research,* ed. J. R. Marrow (New York: Nova Science Publishers), 81–104.

Fisher, M., Gabbay, D., and Vila, L. (2005). *Handbook of Temporal Reasoning in Artificial Intelligence.* Amsterdam: Elsevier.

Guilhardi, P., Keen, R., MacInnis, M., and Church, R. (2005). How rats combine temporal cues. *Behav. Process.* 69, 189–205.

Hasselmo, M. (2009). A model of episodic memory: mental time travel along encoded trajectories using grid cells. *Neurobiol. Learn. Mem.* 92, 559–573.

Hasselmo, M., Giocomo, L., Brandon, M., and Yoshida, M. (2010). Cellular dynamical mechanisms for encoding the time and place of events along spatiotemporal trajectories in episodic memory. *Behav. Brain Res.* 215, 261–274.

Hinton, S. C., and Meck, W. H. (2004). Frontal-striatal circuitry activated by human peak-interval timing in the supra-seconds range. *Brain Res. Cogn. Brain Res.* 21, 171–182.

Iizuka, H., and Ikegami, T. (2004). Adaptability and diversity in simulated turn-taking behavior. *Artif. Life* 10, 361–378.

Ivry, R., and Schlerf, J. (2008). Dedicated and intrinsic models of time perception. *Trends Cogn. Sci.* 12, 273–280.

Karmarkar, U. R., and Buonomano, D. V. (2007). Timing in the absence of clocks: encoding time in neural network states. *Neuron* 53, 427–438.

Karniel, A., and Mussa-Ivaldi, F. A. (2003). Sequence, time, or state representation: how does the motor control system adapt to variable environments? *Biol. Cybern.* 89, 10–21.

Kavounoudias, A., Roll, J. P., Anton, J. L., Nazarian, B., Roth, M., and Roll, R. (2008). Proprio-tactile integration for kinesthetic perception: an fMRI study. *Neuropsychologia* 46, 567–575.

Kimura, H., Hirose, S., Kunimatsu, A., Chikazoe, J., Jimura, K., Watanabe, T., Abe, O., Ohtomo, K., Miyashita, Y., and Konishi, S. (2010). Differential temporoparietal cortical networks that support relational and item-based recency judgments. *Neuroimage* 49, 3474–3480.

Lewis, P., and Miall, R. (2003). Brain activation patterns during measurements of sub- and supra-second intervals. *Neuropsychologia* 41, 1583–1592.

Livesey, A., Wall, M., and Smith, A. (2007). Time perception: manipulation of task difficulty dissociates clock functions from other cognitive demands. *Neuropsychologia* 45, 321–331.

Machado, A., and Arantes, J. (2006). Further tests of the scalar expectancy theory (SET) and the learning-to-time (LeT) model in a temporal bisection task. *Behav. Processes* 72, 195–206.

Maniadakis, M., Tani, J., and Trahanias, P. (2009a). "Time perception in shaping cognitive neurodynamics in artificial agents," in *Proceedings of the International Joint Conference on Neural Networks (IJCNN)*, Atlanta, 2822–2829.

Maniadakis, M., Trahanias, P., and Tani, J. (2009b). Explorations on artificial time perception. *Neural Netw.* 22, 509–517.

Maniadakis, M., Wittmann, M., and Trahanias, P. (2011). "Time experiencing by robotic agents," in *Proceedings of the 19th European Symposium on Artificial Neural Networks Computational Intelligence and Machine Learning (ESANN)*, Bruges, 429–434.

Matell, M. S., and Meck, W. H. (2004). Cortico-striatal circuits and interval timing: coincidence detection of oscillatory processes. *Brain Res. Cogn. Brain Res.* 21, 139–170.

Meck, W. H. (2005). Neuropsychology of timing and time perception. *Brain Cogn.* 58, 1–8.

Medina, J., Carey, M., and Lisberger, S. (2005). The representation of time for motor learning. *Neuron* 45, 157–167.

Nolfi, S., and Marocco, D. (2001). Evolving robots able to integrate sensory-motor information over time. *Theory Biosci.* 120, 287–310.

Pfeifer, R., and Scheier, C. (1999). *Understanding Intelligence.* Cambridge, MA: MIT Press.

Polyn, S. M., Norman, K. A., and Kahana, M. J. (2009). A context maintenance and retrieval model of organizational processes in free recall. *Psychol. Rev.* 116, 129–156.

Roberts, W. A. (2002). Are animals stuck in time? *Psychol. Bull.* 128, 473–489.

Searle, J. R. (1992). *The Rediscovery of the Mind.* Cambridge, MA: MIT Press.

Steels, L. (2003). Intelligence with representation. *Philos. Trans. R. Soc. A* 361, 2381—2395.

Suddendorf, T., Addis, D. R., and Corballis, M. (2009). Mental time travel and the shaping of the human mind. *Philos. Trans. R. Soc. B* 364, 1317–1324.

Sumbre, G., Muto, A., Baier, H., and Poo, M. (2008). Entrained rhythmic activities of neuronal ensembles as perceptual memory of time interval. *Nature* 456, 102–106.

Szelag, E., and Wittmann, M. (2004). Time, cognition, thinking. *Acta Neurobiol. Exp.* 64.

Tani, J. (2004). The dynamical systems accounts for phenomenology of immanent time: an interpretation by revisiting a robotics synthetic study. *J. Conscious. Stud.* 11, 5–24.

Tarlaci, S. (2009). Time, timing and the brain. *NeuroQuantology* 7.

van Gelder, T. (1998). The dynamical hypothesis in cognitive science. *Behav. Brain Sci.* 21, 1–14.

van Wassenhove, V. (2009). Minding time in an amodal representational space. *Philos. Trans. R. Soc. B* 364, 1815–1830.

Varela, F. (1999). Present-time consciousness. *J. Conscious. Stud.* 6, 111–140.

Viard, A., Chetelat, G., Lebreton, K., Desgranges, B., Landeau, B., de La Sayette, V., Eustache, F., and Piolino, P. (2011). Mental time travel into the past and the future in healthy aged adults: an fMRI study. *Brain Cogn.* 75, 1–9.

Wilson, M. (2002). Six views of embodied cognition. *Psychon. Bull. Rev.* 9, 625–636.

Wittmann, M. (2009). The inner sense of time. *Philos. Trans. R. Soc. B* 364, 1955–1967.

Wittmann, M., and van Wassenhove, V. (2009). The experience of time: neural mechanisms and the interplay of emotion, cognition and embodiment. *Philos. Trans. R. Soc. B* 364, 1809–1813.

Wolpert, D. H., and Macready, W. G. (1997). No free lunch theorems for optimization. *IEEE Trans. Evol. Comput.* 1, 67–82.

Woo, S. H., Kim, K. H., and Lee, K. M. (2009). The role of the right posterior parietal cortex in temporal order judgment. *Brain Cogn.* 69, 337–343.

Zakay, D., and Block, R. A. (2004). Prospective and retrospective duration judgments: an executive-control perspective. *Acta Neurobiol. Exp.* 64, 319–328.

Conflict of Interest Statement: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Received: 21 April 2011; paper pending published: 06 June 2011; accepted: 30 August 2011; published online: 19 September 2011.

*Citation: Maniadakis M and Trahanias P (2011) Temporal cognition: a key ingredient of intelligent systems. Front. Neurorobot. **5**:2. doi: 10.3389/fnbot.2011.00002*