Time in Symbiotic Human Robot Interaction

Michail Maniadakis and Panos Trahanias
Foundation for Research and Technology Hellas
N. Plastira 100, Vassilika Vouton, Heraklion
Crete, Greece
{mmaniada, trahania}@ics.forth.gr

ABSTRACT

Contemporary research in human-robot interaction has concentrated on enhancing relevant sensory, perceptual and motor capacities. Along this line, the temporal aspects of human-robot interaction that have been investigated so far consider mainly short-term synchronization issues largely ignoring how successive sessions may be associated over time.

The present paper considers symbiotic human-robot interaction putting emphasis on the close and prolonged partnership and coupling of the two sides. Similar to human-human interactions, the symbiotic paradigm is crucially based on time perception and the development of a common understanding about the past, present and future of the world. We conclude that the equipment of artificial agents with human-like temporal cognition is a prerequisite for accomplishing the long-term goal of human-robot symbiosis.

Keywords

Multimodal Time in Human Robot Interaction, Entimed Cognition, Computational Time Perception

1. INTRODUCTION

The core idea behind symbiotic human-robot interaction regards the close and long-term coupling between humans and artificial agents. However, the inherent temporal dimension of human machine confluence is typically overlooked by contemporary research on human-robot interaction. The majority of existing works consider short-term, almost momentary interactions, isolated from the ongoing and long lasting real world procedures. This is a major barrier for accomplishing symbiotic human robot interaction because artificial agents cannot adequately perceive their operating environment, cannot understand their role in it and thus can hardly adapt to human expectations.

In order to develop robots that are actively integrated into the heavily time-structured human life, artificial agents must be equipped with temporal cognition, a capacity that will render robots capable of considering the temporal properties of human-robot interaction sessions properly linking the latter to the past and the future of the world.

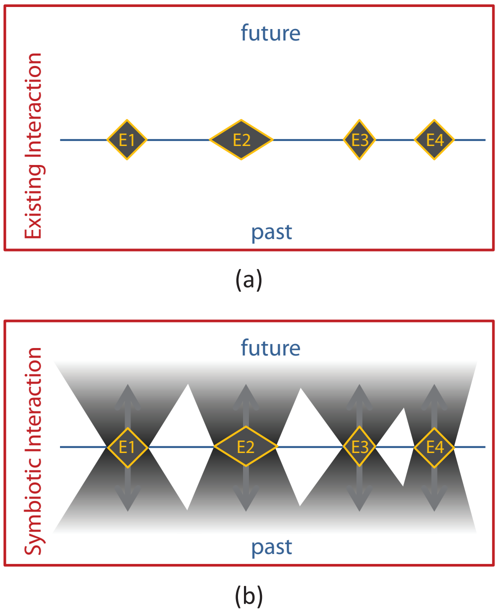

Figure 1: A graphical illustration of the difference between the existing, time-abbreviated human machine interaction that is shown in (a), and what is termed as the symbiotic mode of interaction that spans over the past and future, shown in (b).

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 multiagent interaction are processed,
- in collaborative information processing, where the exploitation of the accumulated information about robots and their human partner facilitates the active engagement of the two sides in comprehensive and productive synergies.

The present paper will focus on the second dimension mentioned above, considering the long-term aspect of symbiotic human-robot interaction.

Despite the fact that humans have conventionally structured their life-time into past, present and future, artificial systems have not so far developed these notions in an adequate level. Even state of the art research on robotic perception considers the world as being 3D rather than 4D structured (i.e. the temporal dimension is largely omitted). As a result, artificial agents are unable to understand long term real world processes and follow the causal relations that associate them over time. This capacity is particularly important for robotic companions, home assistants, care givers, or other systems that interact with humans for extended periods of time. The equipment of robots with temporal cognition is expected to increase their usability by adapting to the emerging (but past- and context- related) requirements of humans.

In the next sections, we discuss the inherent long-term aspects of human robot interaction, and then we make a brief overview of neurophysiological findings on time perception. Subsequently, we discuss the main types of computational models of interval timing, and we outline computational models addressing the interaction of time perception with other cognitive modalities, providing hints on equipping artificial agents with temporal cognition. Finally, we conclude that time plays a key role in implementing human-centered human-robot interaction.

2. ENTIMED COGNITION

Naturalistic human-robot interaction involves a broad set of cognitive functions such as perception, attention, memory storage and recall, future prediction, planning etc. All these cognitive functions incorporate a temporal dimension that crucially enables artificial agents to engage in seamless human robot interaction.

As an example case, consider a robotic assistant that interacts with its owner for the cooperative preparation of 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 environment interaction and real-time dialogue management issues. Moreover, the temporal properties accompanying sense of present act as major driving forces for the time-sensitive planning of robot's actions. For example, time pressure significantly affects the way we choose and express actions. Similarly, in an emergency situation (e.g., barbecue meat is almost burned) the robot must not go for the best solution but for the faster solution.

3. 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 research interest in the neuroscience and cognitive science communities in recent years.

Contemporary review papers and special journal issues have summarized and are testament to the new and burgeoning scientific findings in the field [1, 2, 3, 4]. Evidently, it is now high time to capitalize on these early results and exploit the working principles of the brain towards the equipment of artificial agents with human-like time processing skills.

Over the past decade, a number of different brain areas have been implicated as key parts of a neural time-keeping mechanism in the milliseconds-to-a-few-seconds time range and discussed together with assumed functional properties: notably (among many others), event timing in the cerebellum [5], generalized magnitude processing for time, space and number in the right posterior parietal cortex [6, 7], working memory related integration in the right prefrontal cortex [8, 9], a right fronto-parietal network [10], coincidence detection mechanisms using oscillatory signals in fronto-striatal circuits [11], hippocampal time-cells focused on the relation of time and distance [12], as well as integration of ascending interoceptive (that is, body) signals in the insular cortex [13, 14].

The participation of many brain areas in the processing of temporal information attest the key role of time in multiple aspects of cognition such as decision making, action planning, memory storage and recall, etc. [15, 16, 17].

4. COMPUTATIONAL MODELS OF TIME 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 [18, 19]. The first is the dedicated approach (also known as extrinsic, or centralized) that assumes an explicit metric of time. This is the oldest and most influential explanation on interval timing. 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 [20, 21, 22]. This has inspired the subsequent pacemaker approach that uses oscillations to represent clock ticks [23, 24]. Other dedicated models assume monotonous increasing or decreasing processes to encode elapsed time [25, 26]. The second approach includes intrinsic explanations (also known as distributed) that describe time as a general and inherent property of neural dynamics [27, 28, 29]. 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 [30] and the Learning to Time [31] make explicit coupling between time perception and behavior, assuming that the behavioral vocabulary of subjects and their current behavioral state support duration perception.

The main limitation of the dedicated approach regards its weakness in explaining modality specific differences in time perception. On the other side, intrinsic models are considered to have limited processing capacity, therefore considered inappropriate to accomplish duration processing in complex and real life tasks. However, both modeling approaches are supported by neurophysiological and behavioral observations and the debate concerning the representation of time in the brain is now more active than ever.

An attempt to combine the two 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 [32, 33]. 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 [34]. Moreover, a new integrated model accomplishing generalized duration processing is considered in [35].

4.1 Cognitive models exploiting sense of time

As discussed above, a number of time-dependent cognitive capacities are getting involved in natural multi-agent interactions. Recently, an increasing number of computational models aim at integrating sense of time into cognitive modalities that are relevant to human robot interaction. The following list provides an outline of the existing works.

- **Time in decision making** [36]. Artificial agents self-organize time perception capacity to support decision making.
- **A grounded temporal lexicon** [37]. Lingodroids (language learning robots) are employed to learn terms linking space and time.
- **Mental Time Travel** [38]. Explore the ability to recall and potentially re-experience a previously experienced motion trajectory, by associating specific stimuli with specific memories.
- **Forgetting** [39] . Explaining how working memory evolves and reshapes through time.
- **Memory Reconsolidation** [40]. Episodic encoding based on the binding of events to their temporal context and memory reinstantiation through learning.

We consider again the dinner preparation example (see section 2) to discuss how these capacities can be useful in scenarios of symbiotic human robot interaction. When robot works on an assigned task like “clean the workbench” or “add more salt in the casserole”, it might also be instructed to open the door after a bell ring. In such a case, the robot must consider the expected duration of the given task (5-10 minutes for workbench cleaning but only few seconds for salt addition) to choose whether it should interrupt or not its current activity before opening the door. Additionally, it is quite common for humans to ask about the progress of the scheduled activities (e.g. “will the workbench be ready in the next five minutes?”). Therefore, robotic assistants are necessary to ground time perception on real world activities, being able to make rough estimates about the time remaining for the completion of tasks. To better organize current activities, the robot may recall past sessions of human-robot interaction, improving and correcting things that may have gone wrong (e.g. that one of the visitors does not like sitting close to the fireplace). It is noted that mental time travel regards not only the past but also the future of the world. Therefore, simplistic solutions like considering robot’s log file can by no means implement the full extent of the human mental time travel ability. Interestingly, when humans consider a memorized event, the majority of our past perceptual experiences can not be recovered (i.e. we only recall that the visitor dislikes sitting close to the fireplace but we do not recall the color of the t-shirt he had put on, even if we had perceived it in the past). Forgetting, filters the information encoded in our long-term memory, preserving only the items with high validity for the future. Moreover, when humans point to the robot an event or feature of the past that the robot does not remember, the latter should be able to update its memory and include the supplementary information provided, to be used at a future time (e.g. in addition to avoid the fireplace, the visitor prefers red wine against white wine).

The integration of the above mentioned temporally extended cognitive capacities into a fully entimed system will pave the way for implementing flexible and naturalistic modes of human-robot interaction that resemble human-human interaction. This is certainly not a straight forward procedure, given the heterogeneous computational approaches and the diverse assumptions adopted by the existing works. It is noted however that the pure usage of robot’s clock measures do not guarantee temporal cognition for artificial agents [41]. 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!

To proceed effectively towards implementing artificial temporal cognition, it is necessary to consider the natural, developmental procedure of the human brain that enables different time processing capacities to develop and integrate with other cognitive skills. While primary sense of time capacities mature very early in the human developmental procedure, our temporal cognition skills continuously improve until adolescence [42, 43]. Following a similar incremental 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. Future works along these unpaved pathways are expected to have high impact in developing the next generation of intelligent systems fully integrated into human environments.

5. CONCLUSIONS

Systematic research efforts enabling artificial agents to consider the 4D rather than 3D nature of human robot interaction, are expected to provide new impetus in the way we study and implement intelligent systems. This is because the perception of time will render artificial agents capable of placing their experiences, perceptions and activities on the past-present-future timeline, accomplishing advanced and durable synergetic interaction with humans.

In conclusion, temporal cognition 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.

6. REFERENCES

[1] E. Szelag and M. Wittmann, "Time, cognition, thinking," *Acta Neurobiologiae Experimentalis*, vol. 64, no. 3, 2004.

[2] W. Meck, "Neuropsychology of timing and time perception," *Brain & Cognition*, vol. 58, no. 1, 2005.

[3] J. Crystal, "The psychology of time: A tribute to the contributions of russell m. church." *Behavioural Processes*, vol. 74, no. 2, 2007.

[4] M. Wittmann and V. van Wassenhove, "The experience of time: neural mechanisms and the interplay of emotion, cognition and embodiment," *Phil. Trans. Royal Society B*, vol. 364, pp. 1809–1813, 2009.

[5] R. Ivry and R. Spencer, "The neural representation of time," *Current Opinion in Neurobiology*, vol. 14, pp. 225–232, 2004.

[6] D. Bueti, B. Bahrami, and V. Walsh, "The sensory and association cortex in time perception." *Journal Cognitive Neuroscience*, vol. 20, pp. 1054–1062, 2008.

[7] M. Oliveri, G. Koch, and C. Caltagirone, "Spatialtemporal interactions in the human brain," *Experimental Brain Research*, vol. 195, no. 4, pp. 489–497, 2009.

[8] P. Lewis and R. Miall, "Brain activation patterns during measurements of sub- and supra-second intervals." *Neuropsychologia*, vol. 41, pp. 1583–1592, 2003.

[9] A. Smith, E. Taylor, K. Lidzba, and K. Rubia, "A right hemispheric frontocerebellar network for time discrimination of several hundreds of milliseconds," *Neuroimage*, vol. 20, pp. 344–350, 2003.

[10] D. Harrington, K. Haaland, and R. Knight, "Cortical networks underlying mechanisms of time perception," *Journal of Neuroscience*, vol. 18, pp. 1085–1095, 1998.

[11] S. Hinton and H. Meck, "Frontal-striatal circuitry activated by human peak-interval timing in the supra-seconds range." *Cognitive Brain Research*, vol. 21, pp. 171–182, 2004.

[12] B. Kraus, R. Robinson, J. White, H. Eichenbaum, and M. Hasselmo, "Hippocampal "time cells": time versus path integration," *Neuron*, vol. 78, no. 6, pp. 1090–1101, 2013.

[13] A. Craig, "Emotional moments across time: a possible neural basis for time perception in the interior insula," *Phil. Trans. Royal Society B*, vol. 364, pp. 1933–1942, 2009.

[14] M. Wittmann, "The inner experience of time," *Phil. Tran. Royal Soc. B*, vol. 364, pp. 1955–67, 2009.

[15] A. Livesey, M. Wall, and A. Smith, "Time perception: manipulation of task difficulty dissociates clock functions from other cognitive demands," *Neuropsychologia*, vol. 45, pp. 321–331, 2007.

[16] S. Rao, A. Mayer, and D. Harrington, "The evolution of brain activation during temporal processing," *Nature Neuroscience*, vol. 4, pp. 317–323, 2001.

[17] N. Taatgen, H. van Rijn, and J. Anderson, "An integrated theory of prospective time interval estimation: the role of cognition, attention and learning," *Psychological Review*, vol. 114, no. 3, pp. 577–598, 2007.

[18] D. Bueti, "The sensory representation of time," *Frontiers in Integrative Neuroscience*, vol. 5, no. 34, 2011.

[19] R. Ivry and J. Schlerf, "Dedicated and intrinsic models of time perception," *Tr. in Cognitive Sciences*, vol. 12, no. 7, pp. 273–280, 2008.

[20] H. Woodrow, "The reproduction of temporal intervals," *Journal of Experimental Psychology*, vol. 13, pp. 473–499, 1930.

[21] J. Gibbon, R. Church, and W. Meck, "Scalar timing in memory," in *Timing and time perception (Eds J. Gibbon & L. G. Allan) New York Academy of Sciences*, 1984, pp. 52–77.

[22] S. Droit-Volet, W. Meck, and T. Penney, "Sensory modality and time perception in children and adults," *Behav. Process*, vol. 74, pp. 244 – 250, 2007.

[23] C. Miall, "The storage of time intervals using oscillating neurons," *Neural Computation*, vol. 1, pp. 359 – 371, 1989.

[24] E. Large, "Resonating to musical rhythm: Theory and experiment," in *S. Grondin (Ed.), Psychology of time*, 2008, pp. 189–232.

[25] J. Staddon and J. Higa, "Time and memory: towards a pacemaker-free theory of interval timing," *J Exp Anal Behav*, vol. 71, no. 2, pp. 215 – 251, 1999.

[26] P. Simen, F. Balci, L. deSouza, J. Cohen, and P. Holmes, "A model of interval timing by neural integration," *J. Neuroscience*, vol. 31, pp. 9238–9253, 2011.

[27] V. Dragoi, J. Staddon, R. Palmer, and C. Buhusi,

"Interval timing as an emergent learning property," *Psychol. Review*, vol. 110, no. 1, pp. 126–144, 2003.

[28] U. R. Karmarkar and D. V. Buonomano, "Timing in the absence of clocks: Encoding time in neural network states," *Neuron*, vol. 53, no. 3, pp. 427 – 438, 2007.

[29] J. Wackermann and W. Ehm, "The dual klepsydra model of internal time representation and time reproduction," *Journal of Theoretical Biology*, vol. 239, no. 4, pp. 482–493, 2006.

[30] P. Killeen and J. G. Fetterman, "A behavioral theory of timing," *Psychological Review*, vol. 95, no. 2, pp. 274–295, 1988.

[31] A. Machado, "Learning the temporal dynamics of behavior," *Psychological Review*, vol. 104, pp. 241–265, 1997.

[32] M. Matell and W. Meck, "Cortico-striatal circuits and interval timing: coincidence detection of oscillatory processes," *Cogn Brain Res*, vol. 21, pp. 139–170, 2004.

[33] W. Meck, T. Penney, and V. Pouthas, "Cortico-striatal representation of time in animals and humans," *Current Opinion in Neurobiology*, vol. 18, no. 2, pp. 145 – 152, 2008.

[34] S. Teki, M. Grube, and T. Griffiths, "A unified model of time perception accounts for duration-based and beat-based timing mechanisms," *Frontiers in Integrative Neuroscience*, vol. 5, no. 90, 2012.

[35] M. Maniadakis and P. Trahanias, "Self-organized neural representation of time," in *M. Lee et al. (Eds.): ICONIP 2013, Part I, LNCS 8226, Springer-Verlag Berlin Heidelberg*, 2013, pp. 74–81.

[36] M. Maniadakis, P. Trahanias, and J. Tani, "Explorations on artificial time perception," *Neural Networks*, vol. 22, pp. 509–517, 2009.

[37] R. Schulz, G. Wyeth, and J. Wiles, "Are we there yet? grounding temporal concepts in shared journeys," *IEEE Transactions on Autonomous Mental Development*, vol. 3, no. 2, pp. 163–175, 2011.

[38] M. E. Hasselmo, "A model of episodic memory: Mental time travel along encoded trajectories using grid cells," *Neurobiology of Learning and Memory*, vol. 92, no. 4, pp. 559 – 573, 2009.

[39] K. Oberauer and S. Lewandowsky, "Modeling working memory: a computational implementation of the time-based resource-sharing theory," *Psychonomic Bulletin & Review*, vol. 18, no. 1, pp. 10–45, 2011.

[40] P. Sederberg, S. Gershman, S. Polyn, and K. Norman, "Human memory reconsolidation can be explained using the temporal context model," p. 455468, 2011.

[41] V. Pouthas and S. Perbal, "Time perception does not only depend on accurate clock mechanisms but also on unimpaired attention and memory processes," *Acta Neurobiol Exp*, vol. 64, pp. 367–385, 2004.

[42] S. Droit-Volet, "Child and time," in *In A. Vatakis, A. Esposito, M. Giagkou, F. Cummins and G. Papdelis (Eds.). Multidisciplinary Aspects of Time and Time Perception*, 2011, pp. 151–173.

[43] K. Tucholska and B. Gulla, "Children's time experience and childhood memories legal aspects," in *First International Conference on Time Perspective*, 2012.