FETPROACT-2-2014: Knowing, doing, being: cognition beyond problem solving

ACTION ACRONYM

TIMESTORM

ACTION FULL TITLE

" MIND AND TIME: INVESTIGATION OF THE TEMPORAL TRAITS OF HUMAN-MACHINE CONVERGENCE"

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EXPERIMENTAL AND MODELLING SPECIFICATIONS

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TIMESTORM
Experimental and Modelling Specification

1 Goals and Objectives

TIMESTORM aims at elucidating the crucial role that the sense of time has in human cognition, both in perception and action. The final practical goal is to endow artificial agents with the capacity to experience the flow of time, and shift the focus of human-machine confluence to the temporal aspects of symbiotic interaction. The proposed research and technological developments in time perception will contribute significantly to ongoing efforts in deciphering relevant temporal brain circuitry and will also give rise to innovative implementations of artifacts with profoundly enhanced cognitive capacities.

The experimental research approach adopts a joint developmental, behavioral and neuroimaging investigation of the human brain to decipher the circuits and neuro-functional processes involved in temporal cognition and perception. The research particularly aims at understanding the relationship between temporal processes, memory and cognitive ability. These findings will be used to implement cognitive models that realize diverse aspects of time perception and their links to ordinary cognitive skills. The models will inform the design of a new generation of cognitive systems that will be embodied in humanoid robots and enable them to exploit the sense of time in order to effectively engage in symbiotic human-robot interaction situations.

TIMESTORM work is formulated in such a way that facilitates collaboration and interaction between the experimental and modelling research. In order to achieve this the proposed work has been divided into separate themes, under each of which there is a strong synergy between the proposed experimental and modelling work. In doing so the aim is for each to inform the other, and combine so that each themed facet effectively contributes to the overall TIMESTORM goal.

There are eight experimental and modeling themed research activities. The fundamental aspects of human time perception will be explored, specifically by examination of the effect of temporal context and modal influences on time perception. The study will contribute to the long-standing discussion regarding the existence of a single or many dedicated circuits for time perception. It will do so by 1) deciphering how context is built up over time by finding the neurophysiological signatures of temporal context, 2) performing developmental studies regarding the magnitude of the time distortion between the sensory modalities as a function cognitive ability, 3) exploring the capability of human temporal perception to maintain multiple distinct Bayesian priors for temporal context, 4) investigating how temporal estimates are modulated by a variation in sensorimotor coupling and the feeling of immersion and naturalness. The experimental results will inform the building of models of human subjective responses regarding temporal intervals, and the effects of adaptation of temporal perception due to recent sensory experience. Further experimental work will explore whether time perception is affected by interoception and perceived embodiment. This latter work will be complemented by a neural predictive coding model. The model will help explain the influence of cognitive and emotional factors on the subjective experience of temporal flow.

An important aspect of temporal cognition is its interaction with memory. This will be explored by 1) performing experimental work to discover whether the processing of time directly derives from the basic working memory system, 2) exploring the consolidation of time in long-term memory, and 3) investigating the effect of interference processes on the long-term temporal memory. The resulting findings will contribute to a neurobiologically plausible model of interval timing in which timing is closely linked to the encoding and storage of working memory elements, and a time-driven memory system embodied in a robot that is capable of recalling and processing events and their temporal characteristics.

Neural models will be built to explore questions regarding the flow of time from future to present and from present to past, as well as model temporal scale invariant memory sequence recall. The aim is to endow artificial agents with a human-like understanding of the temporal properties of real world dynamic processes and develop a mechanism that not only supports recalling the past but also investigates how our understanding of past can inform our expectation of the future. How cognitive abilities affect time sensitivity will be investigated through developmental studies. In combination this research will inform the implementation of a temporal cognition system that incorporates the use of time as the cognitive glue that facilitates the interaction between cognitive skills.

Understanding time in relation to behaviour is key to developing robots that can effectively engage with humans. To address this, an experimental study will be made regarding whether temporal aspects of perceiving and manipulating actions depend upon whether they are demonstrated in either the first or third person, or demonstrated by either a “real” or animated actor. The question of temporal durations shall further be explored experimentally in both laboratory and different socio-emotional contexts, as well as in relation to human-robot interaction. Cognitive systems will be developed from this which enable robotic agents to interact in different environments and contexts, and that consider temporal aspects of human-robot interaction, such as fluency of human-robot interaction, temporal planning, and management of personal time.

The TIMESTORM project envelops important issues regarding time perception and its relation to context, modality, interoception and embodiment. It will also uncover how time and other brain processes such as memory and cognitive functions interact, and how the flow of time and its relation to temporal recall and future expectation operates. In addition, temporal action perception and manipulation of behavior will be elucidated. Together this research will contribute to the design of cognitive robotic agents capable of seamless integration in different environments and contexts, and fluent cooperative interaction with humans.

2 Research Activities

2.1 Effect of Temporal Context on Time Perception

2.1.1 Overview

Performance on interval timing tasks is highly susceptible to temporal context effects, known as the Vierordt effect, one of the first findings reported in the timing literature. Proposed experimental work will aim to find the neurophysiological signatures of temporal context and in doing so decipher how context is build up over time. In addition, other experimental work will explore the capability of human temporal perception to maintain multiple distinct Bayesian priors for temporal context, which is a requirement for the idea of multiple sensory-channel-specific clocks. In doing so this latter study will contribute to the long-standing discussion regarding the existence of a single or many dedicated circuits for time perception. These experimental results will inform the building of Bayesian models of human subjective responses regarding temporal intervals, as well as modelling the effects of adaptation of temporal perception due to recent sensory experience.

2.1.2 Experimental work

An influential paper by Jayazeri and Shadlen (2010) demonstrated that the effect of recent temporal context on behavioural reports of subsequent intervals is well described by a simple Bayesian model. Using typical human behavioural testing paradigms the University of Sussex (UoS) will extend this result by exploring the capability of human temporal perception to maintain multiple distinct priors for temporal context, contingent on the sensory signal/content of sensory signal of origin. The existence of such contingent contextual priors is presumably necessary under proposals of human timing mechanisms that invoke the use of multiple sensory-channel-specific clocks and/or contextually rate-scalable clocks. Consequently, this work will contribute to the long-standing discussion regarding the existence of a single or many dedicated circuits for time perception. By specific variations in testing procedure, this experiment will address the degree to which the effect of contextual priors on behavioural reports of duration occurs in a predictive (through altering the behaviour of neural mechanisms that encode time) or post-hoc (through modulation at a response level) way.

Related experimental work will be carried out at the University of Groningen (UoG) in order to underpin the neurophysiological signatures of temporal context. In the experiments participants will be presented with visual stimuli with intervals of 700, 800 and 900ms that, depending on the experimental block, are either the shortest or longest durations. They will then be asked to reproduce these durations by means of a key press. If these intervals are the longest durations, the estimated, subjective durations will be shorter than the objective, veridical durations, and vice versa for the shortest durations. This setup is regularly reported in literature, although in these experiments participants are often over-trained (i.e., participants are trained until no performance increase is observed anymore). Although this provides stable date, it prevents taking into account how this temporal context is built up over time. To overcome this, data will be collected from the very first trial, and not just collected after a certain level of proficiency has been reached. This will allow assessment of how, over the course of two hours of timing, the context is built up. Initial results show that context is built up in just a couple of tens of trials, and that the most recent trial has by far the biggest effect. So context matters, but not in the necessarily the way typically assumed in Bayesian models.

2.1.3 Modelling Work

Results from the UoS behavioral study will be linked with the ongoing work of RF Rhodes on short time-scales (e.g. Rhodes, 2014) to produce a Bayesian model that describes human subjective responses regarding intervals up to the scale of seconds. These results will be linked with work on the effects of recent sensory experience on temporal perception in the context of sensory adaptation. Several recent studies from this area have shown evidence for population codes as the neural mechanism underlying readouts of temporal intervals for both short (< 1s; Roseboom et al., 2015; Roach et al., 2011) and longer (Heron et al., 2011) temporal intervals. To fully describe the functional mechanisms that may be involved in these processes will require extensive collection of human behavioural data (e.g Roseboom et al., 2015; Burr et al., 2009) suitable for the modelling of a comprehensive population code. In combination, this work will provide the basis for a comprehensive model of the readout/response level of temporal estimation in humans for intervals up to the scale of seconds.

UoS will subsequently attempt to link the model both upwards to task settings relevant to TIMESTORM (e.g. social contexts such as turn taking), and downwards to neural mechanisms (e.g., the striatal beat frequency model, spiking models of delayed reinforcement learning, or the Kuramoto beat frequency model). The modelling work and linkage to basic neural mechanisms will involve close collaboration with Imperial College London (ICL).

ICL will build hierarchical neural models of Bayesian inference. Probabilistic population codes (Ma et al, 2006) will be used to encode probability distributions in the exponential family for the firing activity of neural populations. The architecture will be designed to perform Bayesian operations upon the neural firing activity of these neural populations. The architecture will support modular hierarchical configurations so that at the highest level multiple distinct priors for temporal context can be coded, and at the lowest level signals from multiple sensory modalities can be coded as input. In addition the model will combine population codes as the neural mechanism underlying adaptive readouts of temporal intervals. The work aims to produce a detailed neural model to support the UoS exploration into the existence of contingent contextual priors and multiple sensory-channel-specific clocks and/or contextually rate-scalable clocks.

2.2 Modal Influences on Time Perception

2.2.1 Overview

Studies have shown that time sensitivity differs as a function of modality. Some researchers suggest that this phenomenon is due to the speed of different internal clocks for each modality, whilst others suggest that it is linked to cognitive interference in time judgment between, for example, the two types of stimuli. The proposed experimental work will explore this issue by means of developmental studies regarding the magnitude of the time distortion between the sensory modalities as a function of different age groups and their respective cognitive abilities. Further to this, this study will provide additional evidence towards the long-standing discussion regarding the existence of a single or many dedicated circuits for time perception already being explored in Temporal Context (Section 2.1). Other work will examine how temporal estimates are modulated by a variation in sensorimotor coupling and the feeling of immersion and naturalness. This will allow investigation of the complex interaction between sense of agency and temporal perception and action ownership that has previously been experimentally unavailable. The experimental findings will provide neurobiological guidelines for modelling the integration of the different perspectives on time from different modalities, and in doing so enable embodied robotic systems to implement the interaction of time perception from different modalities and cognitive systems.

2.2.2 Experimental Work

Université Blaise Pascal (UBP) will explore the difference in time judgment as a function of sensory modalities of presentation of time and attention allocated to time. Studies have suggested that time sensitivity differs as a function of sensory modality, with time sensitivity being better for the auditory rather than for the visual modality. In addition, when the same stimulus durations are presented in two different modalities (visual, auditory) in the same temporal task, a time distortion emerges with the auditory stimuli being judged longer than the visual stimuli. The causes of this modality-related distortion in time judgment are not clear. Some researchers suggest that this is linked to the speed of internal clock that is different for each sensory modality (specific-modality clock speed). Other researchers suggest that this is linked to cognitive interference in time judgment between the two types of stimuli. In order to discuss this issue, children with limited cognitive capacities can be used as a model. The age-related differences in the magnitude of the time distortion between the sensory modalities (visual vs. auditory) as a function of age groups and their respective cognitive abilities will be tested. In a first study, children and adults will be given a temporal bisection with stimulus durations presented in the form of visual and auditory stimuli. Their cognitive abilities will be also assessed with a small series of short neuropsychological tests (session duration at about 20 mn). In the second study, the children will receive the same task in a single temporal task and a dual task when they must both estimate the stimulus duration and perform a non-temporal task (reaction time task).

In related work, UoS and UoG will deploy virtual, augmented, and 'substitutional' reality methods to examine the impact of immersion and sensorimotor coupling on time perception. There will be an examination of the interaction of factors such as impression of naturalness and feeling of immersion during substitutional reality on perception of time. This will allow comparison with previous results reported from simple stimulus configurations with those found in an immersive, substitutional sensory environment. Initially, the work will build on Van Rijn (UoG) work examining time perception in a semi-immersive driving simulation (van Rijn, 2014). UoS's unique substitutional reality set-up (Suzuki, Wakisaka, & Fujii, 2012) will be used to immerse subjects in a naturalistic environment that couples head movements to visual inputs. This depends on linking pre-recorded omnidirectional video to a head-mounted display (Oculus Rift) equipped with high-fidelity head tracking. The experiment will modulate the play-back speed of the immersive environment and compare passive versus sensorimotor-coupled conditions, with interval timing providing a measure of influence on time perception. Factors such as degree of naturalness of impression (both in temporal and non-temporal aspects), type of motion (motion through a scene such as used by Van Rijn, 2014, or tangential to a scene), and complex spatio-temporal aspects such as acceleration and deceleration within natural scenes, and measure their effect on time perception will be assessed.

These results will be linked with the models developed in simple stimulus scenarios, as described in Temporal Context (Section 2.1). Additionally, previously under-explored areas such as temporal perception under different levels of perceived immersion will be tested. This will allow investigation of the complex interaction between sense of agency and temporal perception through systematic variation of the compellingness of subjective experience and action ownership that has previously been experimentally unavailable.

2.2.3 Modelling Work

Modal effects on time perception are important for the development of computational models that will equip (the inherently multimodal) robotic systems with time perception capacity. Experimental findings will provide insight on the discrimination capacity of different modalities with respect to time, which will guide implementing their computational counterparts. Moreover, artificial temporal cognition is a major goal of TIMESTORM that assumes the integration of the different perspectives on time that has been developed in each modality, as well as the interaction of time perception with other cognitive capacities. Neurobiological guidelines will play an important role in the phase of putting together the partial models that will be developed in the project, resulting into a single and comprehensive cognitive system that will be embodied in the ARMAR robot.

It is expected that the investigation of multimodal interaction in computational systems will contribute in developing a primitive sense of self for artificial autonomous agents through bridging multimodal time perception with the ownership of senses and actions. This will be a key point for implementing the sense of self that will be preserved by the robotic system as time goes by, and will be associated with the experiences and memories of the agent.

2.3 Working Memory, Internal Clocks and Time

2.3.1 Overview

Experimental work in this section will explore whether the processing of time directly derives from the basic working memory system (WM) and the relationship between WM and internal clocks. The relationship between the mechanisms involved in time processing and those involved in WM will be elucidated in order to explain findings that show a significant proportion of inter-individual variability in time sensitivity is due to age-differences in WM. These finding will contribute to a neurobiologically plausible model of interval timing in which timing is closely linked to the encoding and storage of WM elements.

2.3.2 Experimental Work

UBP and UoG will collaborate to explore age differences in time judgment as related to WM. Developmental studies reveal that the age-differences in WM explain a significant proportion of inter-individual variability in time sensitivity. The question is: What are the relationships between the mechanisms involved in time processing and those involved in WM? Some models suggest similar cortical oscillators-based system for the working memory and the internal clock involved in time encoding (Striatal Beat frequency model - Miall, 1989, 1996; Mattell & Meck, 2000, 2004). A question that will be addressed is: Does the processing of time directly derive from basic WM system? The aim of this study is thus to try to model the developmental data obtained in a temporal task with new timing models based on temporal oscillators, and to try to disentangle the role of temporal processes from that of WM processes in participants with different capacities of WM.

UBP and UoG will further study age variation in the speeding up of the internal clock. Some studies have demonstrated that the presentation of a sequence of clicks - at a given frequency - produces a lengthening effect because it increases the speed of the internal clock system. In this study, children and adults will be given a temporal task with and without click of different frequencies to examine the age-related differences in the acceleration of the internal clock speed. Then, these data will be modeled to test the idea of oscillators in time processing at different levels of cerebral maturation and their effects on time judgment when their speed increases.

2.3.3 Modelling Work

UoG will develop a neurobiologically plausible model of interval timing in which timing is closely linked to the encoding and storage of WM elements. This model will be based on the earlier work of Van Rijn (UoG) linking biologically inspired models of interval timing such as the Striatal Beat Frequency model and more traditional models of interval timing such as the Scalar Timing Theory and it's implementation in the ACT-R module of interval timing. Parts of this model will be based on collaborations with, or input from UCL. The close link between interval timing and WM will inform the construction of experiments, a series of which is currently under development. The experiments will explore whether multiple time intervals can be concurrently estimated if the constraints of the

WM system are taken into account; whether assessments of WM-efficiency correlate with timing accuracy, and whether WM-manipulations affect interval timing. Moreover, together with UBP the model will inform the link between WM and interval timing in cognitive development and aging.

2.4 Time and Long-Term Memory

2.4.1 Overview

Experimental studies in to long-term memory will investigate why we obtain a lengthening effect instead of a shortening effect when consolidating time, as well as the effect of interference processes on representation of durations. Related modelling of long-term memory will develop a time-driven memory system capable of recalling and processing events and their temporal characteristics, as well as incorporating forgetting of irrelevant, less valuable information. In addition, a model will be built using deep learning and reservoir computing to model temporal scale invariant memory sequence recall. The aim of the latter is to develop a mechanism that not only supports recalling the past but also investigates how our understanding of the past can inform our expectation of the future.

2.4.2 Experimental Work

Few studies have investigated the long-term memory of durations and their consolidation in memory. Recently Cocenas-Siva, Bueno, Doyère & Droit-Volet (2014) Cocenas-Silva, Bueno & Droit-Volet, (2013) have developed a paradigm allowing the test of consolidation of durations in long-term memory. In this paradigm, the participants learn a standard duration and, after a retention interval of 24 hours, they are presented with comparison durations and must judge the similarity between these comparison durations and the standard duration learned previously. In addition, an interference task is given at different periods during the retention interval. The results showed a difference between the short-term and the long-term memory representation of time, with a representation more variable in the second case, and a lengthening effect for the long-term memory of time and a shortening effect for the short-term memory of time. However, the lengthening effect decreases with the increase of the interval between the interference task and the learning of the standard duration (gradient). The question being investigated in this study is: Why do we obtain a lengthening effect instead of a shortening effect for the long-term memory of time? To respond to this question, UBP will run a study on the interference effect between different durations presented in the learning phase (encoding phase) on the long-term representation of a standard duration. In this study, there will be different groups of participants as a function of number of stimulus durations presented during the encoding phase: (A) the standard duration (4s); (B) the standard duration (4s) and another short duration (0.5s); (C) the standard duration (4s) and another long duration (7.5s); (D) the standard duration (4s) and another short and long duration (0.5s and 7.5s).

In addition UBP will study similarities and differences of durations consolidated in long-term memory as function of durations tested. To date, the paradigm of consolidation of duration in long-term memory has been tested with only one value of duration, i.e. 4 s. This study will use this paradigm to test the generalization of results obtained (Cocenas et al. 2013, 2014) with others durations, i.e. shorter (< 1s) and longer (> 8 s).

In the paradigm of consolidation of durations in long-term memory, only one 15-min interference task has been tested, i.e., the backward digit span task. This task, which requires cognitive resources, disrupted the consolidation of durations in memory (Cocenas et al., 2013, 2014). The effect of interference tasks on the long-term memory representation of durations, is it similar between the different types of interference tasks performed during the retention interval: a phonological versus a visuo-spatial task, and a temporal versus a non-temporal task. UBP will further explore the effect of interference processes on the long-term memory representation of durations as a function of the nature of the interference task. In this study, the paradigm of consolidation of durations in long-term memory will be used, but now a series of different interference tasks will be tested.

2.4.3 Modelling Work

Foundation for Research and Technology Hellas (FORTH) will explore the temporal aspects of knowledge management. This regards encoding and labeling events with time stamps (i.e. time of occurrence and/or duration) in a way that facilitates their recall and processing as a part of a decision making process that guides robot actions (Maniadakis, Trahanias, 2015). Besides the encoding of new experiences, an important part of knowledge management regards forgetting of irrelevant, less valuable information in accordance with the role of the robot at a given context. The plan is to develop a time-driven memory system capable of recalling events and their temporal characteristics. The exploitation of past knowledge will be demonstrated by implementing a robotic assistant that recalls the wine preferences of humans and serves the appropriate bottle of wine on the table.

The question of how time is perceived in multiple scales will be explored in collaboration between ICL and FORTH. Human daily activities are organized around a set of cognitive constructs abstracting different periods of time, such as minutes, hours, days, weeks, months, and years. Despite the fact that some of these notions are defined by the cyclical appearance of environmental cues (i.e. days, years), others have been devised by humans to facilitate social interactions (i.e. minutes, hours, weeks, months). Memory recall is scale invariant such that we are not constrained to remember events that take place over a fixed time scale (say minutes) but can recall events over many time scales (seconds, minutes, hours, days, months, years etc.). In addition, scale mixing occurs when recalling events. A computational model will be built to explore the mechanisms of time abstraction at multiple time scales.

The underlying principle behind the model is that salient sensorimotor features drive memory formation. As such the memory of an event that lasts a few minutes would contain the salient features that were continually present over those minutes, whereas the memory of an event which lasted days would contain the salient features that were continually present over those days. The temporal scale of the memory is not dictated by a clock but instead by the continual presence of salient features which could last an arbitrary amount of time. This implies that memories that are enveloped by longer temporal chunks are more abstract in detail than those that are enveloped by small temporal chunks. The model will use deep learning to obtain salient features at different levels of abstraction. Deep learning has been successfully used to acquire the visual features of commonly occurring objects in unlabelled data (Coates, *et al*., 2012; Le, *et al*., 2012). In addition feature hierarchies are formed with progressively more abstract features being recognized the higher one looks in the network hierarchy (LeCun, 2012). One may infer from this that higher levels of the network hierarchy change their behaviour at slower rates than lower levels. For example, different neurons at one level of the network hierarchy may respond to fairly abstract objects in the environment such as a chair, bed, or table. Combinations of these features will drive neurons at even higher levels to respond to even more abstract features such as bedroom or lounge. As a person moves around their bedroom, for example, neurons at the lower level that respond to objects such as a bed or a chair may activate depending on whether or not they are in the visual field. However, at the higher level the neurons that respond to bedroom will be firing during the whole experience. In this way the properties of neurons at progressively higher levels in the deep learning architecture reflect statistical changes in stimuli at different levels of abstraction and also exhibit temporal scale properties that can be captured. The model will use a reservoir computing paradigm to capture temporal properties at each level in the deep learning hierarchy (Hourdakis, Trahanias, 2011). The key design principle in the model is linking the temporal behaviour at different levels of the hierarchy. In doing so more abstract spatiotemporal properties at higher levels in the hierarchy will aid the recall of more detailed spatiotemporal properties at lower levels in the hierarchy (see Figure 1).

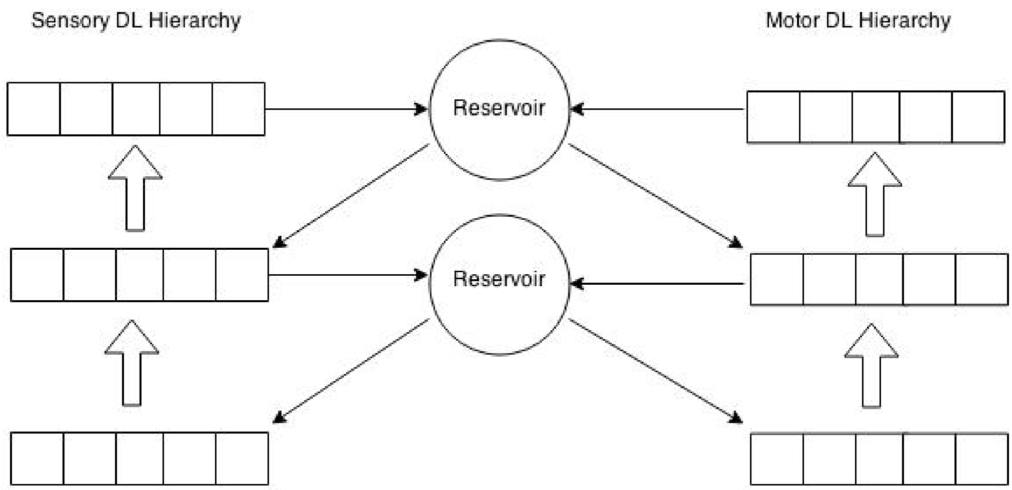

Figure 1. Example architecture incorporating deep learning and reservoir computing for mental time travel.

An important question is: What mechanisms support recalling the past and expecting the future? Human decisions and activities at the present time, are influenced by past experiences and future goals. Therefore, it is important to implement the computational analogous of the underlying influence for robotic systems. The consideration of distant events that will (or have) occur(ed) includes a critical "when" parameter that has to be explicitly acknowledged by artificial agents. The implemented model will endow artificial agents with the ability to perceive the full extent of the timeline that spans both the past and the future and thus acquire a more complete view of the world.

2.5 Interaction of Time and Cognitive Capacities

2.5.1 Overview

The issue of how cognitive abilities affect time sensitivity will be investigated through developmental studies. Differences in time judgment as a function of temporal task, and demand in terms of cognitive abilities required by each task, will be explored in participants of different ages and therefore with different cognitive ability. In related modeling work a temporal cognition system will be implemented that explores mind-time interactions and in doing so investigates the use of time as a cognitive glue which facilitates the interaction between cognitive skills (Maniadakis, Trahanias, 2014). The model will further explore important questions regarding the flow of time, capturing how the moment that was once the present becomes part of the past, and how part of the future, in turn, becomes the new present. The aim is to endow artificial agents with a human-like understanding of the temporal properties of real world dynamic processes.

2.5.2 Experimental Work

UBP will explore the differences in time judgment as a function of temporal tasks and cognitive abilities required by each task: the comparison between children and adults. Studies have shown an improvement in time sensitivity throughout childhood (for a review see Droit-Volet, 2003). The question being asked is: What are the sources of these age-related differences in time sensitivity? The differences in time sensitivity across ages is posited to be linked to the development of the cognitive control abilities that are more or less required as a function of temporal tasks. To test this hypothesis, children aged 5 and 8 years, as well as adults, will be given the 3 temporal tasks that are the most used in human adults: temporal bisection, temporal generalization and temporal reproduction. In addition, the participants' cognitive capacities will be assessed with a series of neuropsychological tests (e.g., forward and backward digit span, Stroop tests). Then, the participants' performance will be modeled to find common factors across the different temporal tasks (variability and distortion in memory representation of time) in order to identify the task that is more demanding in terms of cognitive abilities and the consequences on age-related differences in time judgment in participants with limited cognitive abilities.

UBP will further explore the developmental course of time sensitivity. Developmental studies have shown an improvement of time sensitivity throughout childhood (for a review see Droit-Volet, 2003), suggesting that the sensitivity to time reaches a level close to that found in adults at about 8-10 years old. However, surprisingly enough, no study has tested the improvement of time sensitivity in a wide range of ages. In this study, a great number of children from 3 to 18 years will be given two temporal bisection tasks, one with short durations and the other with longer durations, in order to identify the developmental threshold of stability in time sensitivity.

2.5.3 Modelling Work

FORTH will explore how time interacts with ordinary cognitive capacities. It is really surprising that cognitive capacities have been so far studied in a rather atemporal domain despite the fact that many of them inherently span in time (e.g. memory, attention, action planning, reasoning). The implemented temporal cognition model by FORTH will explore mind-time interactions investigating the use of time as a cognitive glue which facilitates the interaction between cognitive skills. The question of how time moves forward into the future leaving past behind will be further explored by the model. Conventionally, time is divided into three distinct regions; the "past", the "present", and the "future". Using that representational model, the past is generally seen as being immutably fixed, and the future as undefined and nebulous. As time passes, the moment that was once the present becomes part of the past; and part of the future, in turn, becomes the new present. The cognitive model will be able to assimilate the above described cognitive perception of time, and endow artificial agents with a human-like understanding of the temporal properties of real world dynamic processes. This will be achieved by making spatio-temporal abstractions and encoding events at a higher scale. The approach to be followed assumes two coupled subsystems, each one processing different aspects of a hypothetical timeline. The first subsystem assumes a set of neural network components that will integrate real-time sensory-motor information with oscillatory signals to extract information regarding behavior timing. The second subsystem will operate at a higher level encoding abstracted temporal information to be further exploited for the accomplishment of human-robot cooperative tasks. A continuous time flow is assumed in the form shown in Figure 2. A distant moment is the future is gradually approaching the present, and then it gradually becomes distant past.

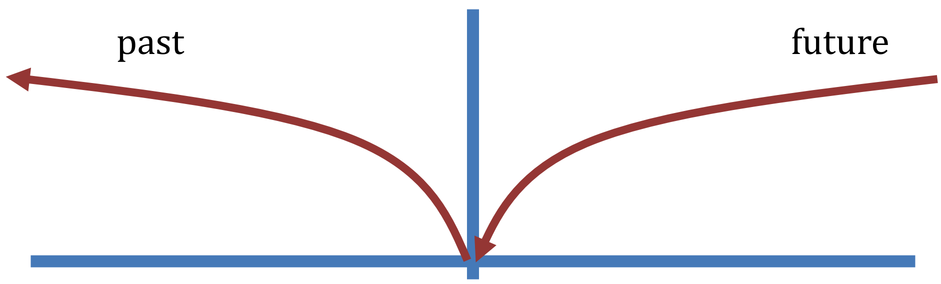

Figure 2. The interaction of past, present and future.

2.6 Time and Embodiment

2.6.1 Overview

Experimental work will explore whether duration judgements are affected by interoception and perceived embodiment. The work will determine individual differences in multiple axes of interoceptive sensitivity (detection, awareness, sensibility), as well as alter the properties of experienced embodiment [e.g. changing experienced body size or shape). In order to further explain the influence of cognitive and emotional factors on the subjective experience of temporal flow and duration, a complementary neural predictive coding model will be build that involves top-down interoceptive predictions counterflowing with bottom-up prediction errors.

2.6.2 Experimental Work

UoS will explore the possible role of interoceptive signals in generation of duration estimates. In collaboration with UoG and UBP the question of whether duration judgements are affected by heartbeat timing, which would reveal an important interoceptive influence, will be asked. The study will also determine precisely what aspects of heartbeat timing influence temporal perception, from basic properties such as general heart rate (linked to general arousal), cardiac period dynamics (Meissner & Wittmann, 2011), and cardiac phase during onset/offset of the to-be-estimated interval (e.g. systole/diastole at onset/offset). Initially the study will focus on this latter direction, extending existing paradigms developed by UoS, which test the impact of stimulus locking to cardiac phase Garfinkel et al, 2014). The study will also analyse the results in terms of individual differences in multiple axes of interoceptive sensitivity (detection, awareness, sensibility), which UoS have already shown to dissociate empirically (Garfinkel, Seth, Barrett, Suzuki, & Critchley, 2015). Further experiments in this domain use virtual and augmented reality setups allowing alteration of the properties of experienced embodiment [e.g. changing experienced body size or shape, (see Suzuki, Garfinkel, Critchley, Seth, 2013). Results from these experiments will expand our understanding of the interaction between interoceptive signals and time perception generally (Maniadakis, Trahanias, 2015) and will be linked to our theoretical work via developing 'predictive processing' theories of interoception and self-experience (Seth, 2013).

Studies on the embodiment of time have shown time distortions when people see pictures of static postures. Recently, Fayolle and Droit-Volet (2014) revealed that the time distortions in emotional contexts are greater with dynamic than static stimuli (pictures). The problem of studies on time perception is that they use emotional pictures that are not real enough to produce temporal distortions similar to those observed in everyday life. Therefore, the aim of a study by UBP and UoS is to try to develop a new paradigm for studying the embodiment of time with situations of virtual reality.

2.6.3 Modelling Work

The UoS study of interoception will provide a novel explanatory framework for the sense of body ownership and selfhood (Seth; 2013). It will investigate how this new concept, which involves top-down interoceptive predictions counterflowing with bottom-up prediction errors, explains the influence of cognitive and emotional factors on the subjective experience of temporal flow and duration. Complementing this experimental work with computational modelling ICL will develop a model of neural predictive coding. The underlying assumption of predictive coding is that the system tries to learn an internal model of the environment (or this case the self) and uses this model to actively predict incoming signals (Huang & Rao, 2011). Whilst predictive coding models exist that use rate based neurons, at present no effective equivalent exists for spiking neurons. The ICL model will address this. In addition to providing the underlying framework for self-modelling, combining such functionality with the efficiency of spike-time coding holds the promise of superior information processing capabilities.

2.7 Time and Behaviour

2.7.1 Overview

The work in this section explores temporal aspects of perception and action. Experimental studies will investigate the manipulation of actions demonstrated by the human. The analysis procedure will not only parse motion characteristics such as trajectory and velocity profiles but also employ semantic object-object and object-body relations. In doing so it will provide an accurate estimation of both length and order of the temporal information for action primitives (Maniadakis et al., 2009). These data will then be used to investigate how subjects perceive the durations of actions, when viewed in either the first or third person, and whether the perceived durations depend on whether the actions are demonstrated by “real” or animated actors. Related modeling work will use the initial experimental data for temporal resource management. In addition models of time will be used for the seamless integration of robotic agents in different environments and contexts.

2.7.2 Experimental Work

KIT will perform experimental work that investigates a set of manipulation actions demonstrated by the human. The main intent is to capture accurate human motions for various periodic (e.g. mixing) as well as non-periodic or single occurrence (e.g. pushing) actions together with the movements of manipulated objects in the scene. The recorded actions will be then analyzed for estimating the temporal length of each action primitive to be further simulated with the robot ARMAR-III by employing the concept of Object-Action Complexes (OACs).

Various actions that involve grasping issues on different objects will be analyzed. The action set will contain “pick & place”, “push”, “mix”, “put in”, “put on”, “take down”, and “cut”. Each action type will be demonstrated by a human subject at least 5 times with various objects at different speeds (fast, slow, and normal). All demonstrations will be recorded with a marker-based motion capture system, working at 100 Hz with the error of less than 1 mm. Recorded human demonstrations will be encoded with the concept of Master Motor Map (MMM), which is a generic mapping framework allowing a unified representation and transfer of whole-body human motions to humanoid robots (Terlemez et al., 2014). Given the MMM representation of the demonstrated action, individual primitives will be parsed (e.g. “approach”, “grasp”, “withdraw”, etc) by considering not only motion characteristics (such as trajectory and velocity profiles) of the hand but also by employing semantic object-object and object-hand relations based on the method in (Wächter and Asfour, 2015). This parsing operation will yield an accurate estimation of both length and order of the temporal information for each action primitive. KIT will take the given the extracted high-level primitives, and attempt to augment the action representation with temporal perception.

These data will be used by KIT to collaborate with UoG in order to compare the perception of time durations, in the above mentioned actions, demonstrated by humans. The MMM representation of each recorded human action will be animated from the first- and third-person viewpoints in the ARMAR-III robot simulator. Two experiments will be conducted in order to investigate how subjects perceive the durations of different OACs, and whether the perceived durations depend on (a) the person performing the OAC is animated or a "real" person, and (b) whether the action is seen from a first or third person perspective.

2.7.3 Modelling Work

KIT will take the given the extracted high-level primitives from their experimental work mentioned above, and attempt to augment the action representation with temporal perception, in other words with the temporal resource management. The action segmentation approach will be simulated using a spiking neural network. In a simulated environment, the robot has to learn how to organize the temporal order of various parallel and sequential action streams to achieve a complex task, e.g. "setting a table", by considering all possible interruptions in the scenario. Second, the parsed primitives will lead to the generalization of the concept of time by means of transferring the observed time duration from one action to another.

In related work, FORTH will explore how the perception of time interacts with embodied sensory-motor processes. Despite the fact that embodiment has been so far investigated from an atemporal point of view, many critical parameters of robot-environment interaction encompass clear temporal characteristics. These may regard the precise timing of activities, the perception of simultaneity and the ordering of events, the adaptation of ordinary behaviors (e.g. speed up) to comply with the special characteristics of emergency situations. The implemented model will directly address the temporal aspects of perception and action emphasizing the use of time for the seamless integration of robotic agents in different environments and contexts.

2.8 Time in Human Robot Interaction

2.8.1 Overview

To date, the perception of long durations of greater that 60 seconds has never been systematically investigated, and has consequently been presumed to conform to timing models for smaller durations. This question of long durations shall be explored in both laboratory and different socio-emotional contexts, as well as in relation to human-robot interaction. Modelling work will consider temporal aspects of human-robot interaction such as fluency of human-robot interaction, temporal planning, and management of personal time.

2.8.2 Experimental Work

The studies on the perception of time in humans have investigated the perception of time in the range of short durations of few milliseconds to several seconds. They have then supposed that the processes involved in time judgment are similar for all duration ranges, and proposed a general internal clock model for the processing of short and long durations. However, to date, the perception of long durations (> 60 s) has never been systematically investigated, and one cannot conclude on the generalization of current timing models for all durations. This lack of studies on the perception of long durations is very surprising because the long durations are characteristics of intervals experienced by humans in daily life. It is also important to examine the perception of long durations in the context of interaction between robots and humans. Consequently, two studies will be run by UBP and FORTH: one with the temporal bisection task in laboratory and different duration ranges, i.e. shorter and longer than 60 s, and the other in the daily life with a series of temporal intervals delimited by two auditory stimuli that the participants have to estimate and that are delivered by smartphones.

Humans' perception of time in the context of interaction with robots will also be studied by UBP and FORTH. The judgment of time in humans is highly sensitive to socio-emotional context. In the human-robot interaction context, the human must wait until the robot has finished executing the instructions. But the wait interval can be difficult to bear for humans because the wait interval is judged too long. The important question being asked is: What are the specificities of humans' time judgment in front humanoid robots? A study will be conducted on the judgment of time in humans when they are perceiving a series of action durations produced by either a robot or a human.

2.8.3 Modelling Work

Capitalizing on the FORTH's aforementioned time perception model, FORTH will explore the temporal aspects of human-robot interaction, considering mainly the following topics:

- fluency of human-robot interaction: specific experiments will address collaborative and turn-taking tasks such as putting all necessary ingredients in the saucepan.
- temporal planning: experiments will address temporal constraints (e.g. perform an action after another) and temporal goals (e.g. to be completed in 2 minutes), in order to optimally schedule robot activities.
- management of personal time: experiments will address situations where the robot is not explicitly assigned any duties for a certain period of time and it is therefore free to decide how to spend its "free" time in a way that is most valuable to humans.

3 Overall Design

As detailed in the Research Activities above, experimental work on TIMESTORM is closely linked to modeling work. The aim is for each to inform the other. For example, the experimental study into human time perception will examine the effect of temporal context (Section 2.1.2) and modal influences (Section 2.2.2) on time perception as well as whether time perception is affected by interoception and perceived embodiment (Section 2.6.2). An initial complementary Bayesian model of human subjective responses regarding temporal intervals will be built (Section 2.1.3). In addition, a population code model of the effects of adaptation of temporal perception due to recent sensory experience will be built (Section 2.1.3). These models will assess the reliability of existing hypotheses examined in the experimental work, and provide new hypotheses for testing. Preliminary work from UoG suggests that context is built up in just a couple of tens of trials, and that the most recent trial has by far the biggest effect. So context matters, but not in the way typically assumed in Bayesian models. In contrasting these experimental and modeling activities the aim is to reconcile these contradictory hypotheses. The resolution of this issue will aid in combining the models to provide a new innovative complete system (Section 2.1.3) in which to test the new hypotheses. From this combined model, a detailed and novel biologically plausible spiking neural predictive coding architecture will be developed (Section 2.6.3) that will further help explain findings regarding the influence of cognitive and emotional factors on the subjective experience of temporal flow.

Another piece of work aims to build a neurobiologically plausible model of interval timing (Section 2.3.3) in which timing is closely linked to the encoding and storage of working memory elements. In order to effectively do this, human data will be exploited from the experimental work regarding the interaction of working memory with time (Section 2.3.2), and in doing so enhance the biological reliability of this model.

Different studies in TIMESTORM will also inform each other. For example, the experimental study in the effect of temporal context on time perception (Section 2.1.2) and the experimental study on modal influences on time perception (Section 2.2.2) both contribute to the long-standing discussion regarding the existence of a single or many dedicated circuits for time perception.

In order to achieve the final goal of building robotic agents capable of interacting in different environments and contexts as well as with humans, the developed cognitive systems will need to leverage data and findings from all the studies detailed above. For example, the experimental study regarding temporal aspects of perceiving and manipulating actions by an actor (Section 2.7.2) will directly inform how a robot perceives its human counterpart and therefore how it manipulates action primitives in order to interact fluently. This will also in part be addressed in studies on collaboration and turn-taking tasks, temporal planning, and management of personal time (Section 2.8.3).

The overall work in time perception, the interaction of time with other cognitive processes, temporal recall and future expectation, and temporal perception and manipulation of behavior, constitute a composite whole within which both experimental and modeling work aim to complement each other. In addition, all facets directly contribute to the final goal of achieving symbiotic robot-human interaction in different environments and contexts.

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