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DELIVERABLE D4.1 [PRELIMINARY VERSION OF THE DELIVERABLE: INTERMEDIATE RESULTS ON TIMELY ACTION PLANNING HUMAN BRAIN MECHANISMS] DUE DATE [JANUARY 1ST, 2016]

> RESPONSIBLE PARTNER [Universite Blaise Pascal Clermont-Ferrand II]

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Preliminary Version of the Deliverable : Intermediate results on timely action planning human brain mechanisms

1 Introduction

Time perception in conjunction with environment cues plays a key role in the planning and execution of actions. Humans schedule and implement tasks differently when they are under psychological pressure, when they are in hurry or they are bored. In the first year of TIMESTORM, a series of experiments have been conducted and some others are under development to investigate the fusion of temporal information with external parameters that may affect behavior. More specifically, our experiments was/are aimed to reveal how humans perceive time and make duration estimations in social contexts that may also involve task execution. Parallel modeling activities were aimed to consider experimental results obtained in order to develop human-like artificial perception for artificial systems.

The following sections summarize completed and ongoing research works, some of them already published or submitted for publication in scientific journals and conferences. The full versions of the relevant works are also included in the Appendix section of the present document.

2 Human studies investigating time in action planning

2.1 The effect of body and emotions on time perception

It is now well established that emotion and bodily activities affect time perception in humans. However, their combinatorial effect on time judgments and the types of emotion that cause larger temporal distortions in time judgment has not been sufficiently explored until now. In this context, UBP examined the effects of emotional bodily expressions on the perception of time. Participants were shown bodily expressions of fear, happiness and sadness in a temporal bisection task featuring different stimulus duration ranges. From a broader point of view, these may correspond to actions that the subjects are enthousiastic or unwilling to participate. Stimulus durations were judged to be longer for bodily expressions of fear than for those of sadness, whereas no significant difference was observed between sad and happy postures. In addition, the magnitude of the lengthening effect of fearful versus sad postures increased with duration range. These results suggest that the perception of fearful bodily expressions increases the level of arousal which, in turn, speeds up the internal clock system underlying the representation of time. The effect of bodily expressions on time perception is thus consistent with findings for other highly arousing emotional stimuli, such as emotional facial expressions. This work has been published in the paper Droit-Volet, S., & Gil, S. (2015). The Emotional body and time perception. Cognition & Emotion, 1-13, which is fully included in the Appendix at the end of the present document.

The obtained results provide important hints on modeling time perception mechanisms and implementing artificial agents that experience the flow of time in a way similar to humans.

2.2 Time perception for long durations

The vast majority of research efforts that have been devoted on time perception has been so far directed on the investigation of interval timing in the range of a few milliseconds or seconds. The examination of temporal judgments for long durations (Dj) and their relation with the judgment of time passage (PTj), is a research topic that has been totally neglected until now. However, in complex real-world setups human activities additionally assume processing of time in the scales of minute, hour, day, etc. In the context of TIMESTORM, UBP research aims to cover this gap by exploring how humans perceive and process long duration judgments in daily life. This experiment did not show any relation between the PTj and Dj. A second experiment was currently conducted to examine this relation with durations longer than those tested (> 1 s). This work has been recently accepted for publication in the paper *Droit-Volet, S. & Wearden, J. Passage of time judgments are not duration judgments: Evidence from a study using Experience Sampling Methodology. Frontiers in psychology.* The full paper is included in the Appendix, at the end of the present document.

A third experiment in collaboration with FORTH is on the way aiming to test Dj with very long durations, in a very naturalistic, real life context.

2.3 Timing in real world action sequences

In order to study behavior timing in naturalistic conditions, the University of Groningen and the Karlsruhe Institute of Technology designed an experiment in which human observers were presented short movie clips of an artificial agent was performing a number of everyday household tasks. In each video, the agent walked towards the table to pick up an object which was required for the action, and then performed the action. Importantly, there were no clearly indicated starting and ending points of the actions and tasks. The instruction to the participant was to time the task, and to reproduce the duration of the task after the video had ended.



Figure 1. Mean reproduced action durations. Mean reproduced durations for each action (short and long version of an action are labeled with [s] and [l]), averaged over all participants. Violin plots illustrate the density distributions of participants' responses, i.e., reproduced action durations. Grey dots depict the objective duration as defined by the SEC algorithm. Generally, shorter durations were overestimated and longer durations underestimated, hinting at typical context effects. (Figure taken from submitted paper).

The relevant work has been submitted for publication in a joint UoG-KIT paper *N. Schlichting, A. Damsma, E. E. Aksoy, M. Wächter, T. Asfour, H. van Rijn, Temporal Context Influences the Perceived Duration of Everyday Actions* as shown in the appendix. Further details of this study can be found in the appendix, but most importantly, participants seemed to have no problems performing this task although their responses, as shown in Figure 1, were more variable than in more controlled settings. Even though it was quite different from existing interval timing tasks, all typical interval timing phenomena were observed, such as the scalar property but also the dependency on the previous, just-experienced, durations.

3 Computational models of time-informed actions

The equipment of artificial agent with temporal cognition is a major goal of TIMESTORM research. To this end, FORTH has investigated brain-inspired paradigms that facilitate the representation and further processing of time, in support to decision making procedures for artificial cognitive systems. Two different modelling directions have been explored in parallel, as summarized below.

3.1 Interval timing in multiple behavioral contexts

A first model neural network model was implemented with the important advice of partners UBP and UoG summarizing the pros and cons of the widely referenced in the literature intrinsic [Dragoi et al., 2003; Karmarkar & Buonomano, 2007] and dedicated [Droit-Volet et al., 2007; Simen et al., 2011; Staddon & Higa, 1999] representations of time. Our work aimed at putting time perception in a behavioral context and thus explores how the processing of time can be useful to other cognitive capacities. In short, the model is implemented through an evolutionary design procedure, making a very limited set of a priori assumptions regarding its internal structure and machinery. Artificial evolution facilitates the unconstrained self-organization of time representation and processing mechanisms in the brain of simulated robotic agents. A particularly interesting characteristic of the present study regards the implementation of a single computational model to accomplish not only one but three different behavioral tasks that assume diverse manipulation of time intervals, therefore enabling the multifaceted exploration of duration-processing mechanisms. Careful examination of the artificial brains has shown that the implemented mechanisms incorporate characteristics from both the 'intrinsic' time representation scheme and the 'dedicated' time representation scheme. Even though these two schemes are widely considered as contradictory, the present study shows that it is possible to effectively integrate them in the same cognitive system. This provides an important framework for equipping artificial agent with a time perception capacity that can be further exploited in a usable manner in behavioral contexts. This work has been published in M. Maniadakis, P. Trahanias, (2015), Integrated Intrinsic and Dedicated Representations of Time: A Computational Study Involving Robotic Agents, Timing & Time Perception, 3(3-4), 246 – 268. A full version of the paper is included in the end of the present document.

3.2 A framework of time representation that facilitates processing of external factors

It is now well established in the literature that the perception of time can be largely affected by external factors such as emotions. However, the way time is currently used in robotic systems assumes a rather fragile representation of temporal information. Time is separately processed in dedicated modules without the ability to be fused with other non-temporal parameters. More specifically, Simple Temporal Networks (STNs) [Morris et. al., 2001] provide the basis to deal with temporal constraints in planning problems. They consist of a set of variables E1 En representing executable events that are properly linked with edges Ei ->Ej indicating that Ei is a prerequisite for the occurrence of Ej. Each edge Ei ->Ej is labeled by an interval [aij, bij] which states that passing from Ei to Ej takes minimum aij and maximum bij moments. Following this formulation, previous works have considered back propagation rules to dynamically preserve dispatchability of plans [Shah et al., 2007], address temporal problems with choice [Shah and Williams, 2008], or reason between interacting agents [Boerkoel and Durfee, 2013].

A common limitation of these works, regards the treatment of time in isolation, without the ability to jointly consider other cognitive components that may affect the consideration of time. In this context, we put forward a new modeling framework that assumes the representation of time intervals as fuzzy numbers that can be easily combined with non-temporal factors to simulate time perception deficits. Our ongoing research explores the possibility of representing emotional states by fuzzy sets that may correspond to fear, normal, happy. Fuzzy calculus will then provide a systematic means for mixing the emotional state with time estimations to represent deficits in temporal cognition. This research direction is in the centre of the ongoing collaboration between TIMESTORM partners UBP and FORTH. The joint research goal regards implementing a computational model that sufficiently explains human data on time perception.

In addition to the above, FORTH in collaboration with KIT has explored the potential of using fuzzy numbers to represent time in order to enforce synchrony in multi-agent collaboration setups. More specifically, the use of fuzzy calculus enables processing, assessing and ranking alternative planning scenarios to select the one resulting into the most productive multi-agent collaboration. Interestingly, the proposed framework enables monitoring the execution of the plan from a temporal point of view and take measures (e.g. speed up) in the case of delay. Moreover, by mixing temporal information with other quantitative aspects of multi-agent collaboration, such as robustness of task execution for different agents, quality of task implementation, fatigue (in the case of human participants) it is possible to design and implement complex plans that take into account the individual characteristics of participants.

The efforts devoted on the particularly promising research direction described above, resulted in one paper submission by FORTH, and one joint submission by FORTH and KIT. More specifically, current paper submissions are as follows:

M. Maniadakis and P. Trahanias, A Fuzzy Perspective on Time-Informed Multi-Robot Synchronization, submitted in the 25th Int. Joint Conference on Artificial Intelligence IJCAI-16.

Abstract

Timely interaction is a key topic for multi-robot systems operating in the real world. The present work puts forward a new approach for multi-robot synchronization that is based on representing temporal constraints as fuzzy numbers. By using fuzzy arithmetic it is possible to process temporal constraints, analyze their relations, detect temporal gaps, and additionally develop corrective measures that minimize these gaps. While previous works accomplished multi-robot synchronization by delaying faster agents, the proposed approach aims at a more balanced execution that considers a modified, less time-consuming execution of tasks by the slower agents. In particular, the present study addresses temporal planning by directing the robotic agents to (i) adapt their speed to accomplish task execution

and, (ii) carry out simplified, yet acceptable, versions of the assigned tasks at faster speeds. The latter adaptations fit particularly well with the fuzzy theoretic approach that enables the direct calculation of their effects on the temporal plan. Accordingly, more efficient synchronization is accomplished in multi-robot coordinated task execution.

M. Maniadakis, E. Hourdakis and P. Trahanias, Time-Informed Task Planning in Multi-Agent Collaboration, submitted in the 25th Int. Joint Conference on Artificial Intelligence IJCAI-16.

Abstract

Human-robot collaboration requires the two sides to coordinate their actions in order to better accomplish common goals. In such setups, the timing of actions plays a key role for the quality of the collaborative performance. The present work proposes a new framework for planning multi-agent interaction that is based on the representation of tasks sharing a common starting and ending point, as petals in a composite daisy graph. Coordination is accomplished through temporal constraints linking the execution of tasks. The planner distributes tasks to the involved parties sequentially. In particular, by considering the properties of the available options at the given moment, the planner accomplishes optimal task assignments to agents. Optimality is supported by a fuzzy theoretic representation of time intervals which enables fusing temporal information with other quantitative HRI aspects, therefore accomplishing a ranking of the available options. The current work aims at a systematic experimental assessment of the proposed framework is pursued, verifying that it can successfully cope with a wide range of HRI scenarios.

M. Maniadakis, E. Aksou, T. Asfour, and P. Trahanias, Collaboration of Heterogeneous Agents Through Incremental Planning in Time Constrained Tasks, submitted in the Robotics: Science and Systems (RSS) conference 2016.

Abstract

In many applications, task execution by a coordinated team of robots that feature different skills and competencies, offers certain advantages over a single robot. To better coordinate individual actions, effective planners are necessary to consider the time that agents devote to the completion of partial activities, the different skills that agents may have and the qualitative differences in action implementation by different agents. Multi-agent collaboration in everyday environments assumes the coordination of individual activities in the presence of external disturbances. In this context, incremental approaches seem more appropriate for planning multi-agent collaboration offering increased flexibility against dynamic changes. We propose a new time-informed planning framework for incrementally guiding a team of heterogeneous robots. The proposed approach, takes into account the skills and limitations of individual agents in order to assign them tasks which improve their usability for the team and facilitate the accomplishment of the common goals.

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Appendix

In the following pages, we include the full version of the papers published by partners UBP and FORTH as part of the ongoing TIMESTORM research.

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The emotional body and time perception

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The emotional body and time perception

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We examined the effects of emotional bodily expressions on the perception of time. Participants were shown bodily expressions of fear, happiness and sadness in a temporal bisection task featuring different stimulus duration ranges. Stimulus durations were judged to be longer for bodily expressions of fear than for those of sadness, whereas no significant difference was observed between sad and happy postures. In addition, the magnitude of the lengthening effect of fearful versus sad postures increased with duration range. These results suggest that the perception of fearful bodily expressions increases the level of arousal which, in turn, speeds up the internal clock system underlying the representation of time. The effect of bodily expressions on time perception is thus consistent with findings for other highly arousing emotional stimuli, such as emotional facial expressions.

Keywords: Timing; Time perception; Emotional body; Bodily expression; Emotion.

The ability to understand the emotions expressed by others is an important aspect of human social cognition, not least because it allows people to predict others' actions and to adapt their own behaviour accordingly (Frijda, 1988; Levenson, 1994). Regarding the critical role of emotion in adaptive actions, studies conducted in the past decade have revealed a tight coupling between the emotionality of stimuli and their apparent duration (Droit-Volet & Meck, 2007). Timing ability in humans is often attributed to an internal clock-like system that provides the raw material (time units) for making accurate time judgments (Allman, Teki, Griffiths, & Meck, 2014; van Rijn, Gu, & Meck, 2014). However, when they are exposed to emotionally charged stimuli, people exhibit distorted time judgments. In this so-called *time-emotion paradox* (Droit-Volet & Gil, 2009), even though individuals possess a sophisticated mechanism for processing time accurately, their time judgments are biased by the perception of emotional stimuli. This emotional distortion in the subjective estimation of time is assumed to reflect the automatic processing of emotional stimuli by the organism for readiness of action (Droit-Volet, Fayolle, Lamotte, & Gil, 2013). Given that emotional bodily expressions can be regarded as a raw and efficient channel of emotional information (de Gelder, 2006, 2009), we investigated for the very first time whether they can trigger the time distortion effect.

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Researchers examining emotional time distortion in humans have made extensive use of emotional facial expressions (e.g., Bar-Haim, Kerem, Lamy, & Zakay, 2010; Doi & Shinohara, 2009; Droit-Volet, Brunot, & Niedenthal, 2004; Fayolle & Droit-Volet, 2014; Gil & Droit-Volet, 2011b; Tipples, 2008, 2011). Consistent with the literature on emotion, they have regarded facial expressions as primary signals of emotion in social interactions (de Gelder & Hortensius, 2014). However, as Darwin (1872/2002) suggested long ago, individuals use multiple emotional cues in their social interactions, including not just facial expressions, but prosody and bodily expressions, too. Investigating these different emotional cues can therefore give us a broader and more comprehensive view of emotion processing. Several studies have shown that bodily expressions are recognised by individuals as easily as facial expressions (e.g., de Gelder, Snyder, Greve, Gerard, & Hadjikhani, 2004), and event-related potential studies have revealed that they are processed as quickly as facial expressions (e.g., Van Heijnsbergen, Meeren, Grezes, & de Gelder, 2007). However, despite the similarities between facial and bodily expressions in the communication of emotion, there is one fundamental difference. As stated by de Gelder (2009, p. 3478), "focusing on facial expressions tends to make us refer to a person's mental state. But focusing on bodily expressions directs attention to a person's actions". Bodily expressions therefore represent the major action component of emotion. Indeed, the whole human body and its motion indicate to the observer the individual's intended action. Consequently, if action readiness is a critical factor in emotion-related time distortion, it is important to examine the effects of emotional postures on the perception of time.

Action readiness is nevertheless governed by the perception of discrete emotions (Frijda, 1988). It is at its strongest in threatening situations. Facial expressions of fear in conspecifics signal the presence of some kind of threat (e.g., Adolphs, Russell, & Tranel, 1999; Ledoux, 2014; Morris et al., 1996). Their perception therefore automatically triggers a series of physiological changes in the observer so that he/she is able to react as quickly as possible (i.e., to flee). Functional magnetic resonance imaging (fMRI) studies have shown that the perception of facial expressions activates the amygdala, a basal ganglia structure involved in the processing of threatening stimuli (Ledoux, 2007; Phelps & Ledoux, 2005). The first fMRI study to feature bodily expressions of fear, conducted by Hadjikhani and de Gelder (2003), revealed activation of the same structure. Facial and bodily expressions therefore both activate a brain region involved in the avoidance motivation system for action (Cacioppo & Berntson, 1994; Lang, Bradley, & Cuthbert, 1997; Ledoux, 2012). There are thus similarities in the physiological and neural changes that take place in individuals when they see the face or the whole body of a conspecific expressing the emotion of fear (e.g., de Gelder, 2006; Tamietto & de Gelder, 2010; Tamietto et al., 2009). We can therefore assume that the perception of bodily expressions of fear produces distortions in time judgment just as the perception of facial expression of fear has been found to do.

Time distortions induced by facial expressions have mainly been investigated in studies featuring a temporal bisection task (e.g., Droit-Volet et al., 2004; Gil & Droit-Volet, 2011a; Tipples, 2008, 2011). In bisection, participants are initially shown a neutral oval form for a short (400 ms) and a long (1600 ms) standard duration. They are then shown emotional faces for durations that are either equal to the short or long standard durations or of intermediate durations and asked to judge whether these comparison durations are more similar to the short standard duration or to the long one. The results of bisection tasks have systematically shown that angry or fearful faces are judged to be displayed for longer than happy, sad or neutral faces (e.g., Droit-Volet et al., 2004; Fayolle & Droit-Volet, 2014; Gil & Droit-Volet, 2011a; Tipples, 2008, 2011). However, the magnitude of this lengthening effect is smaller for angry/fearful versus happy faces than it is for angry/fearful versus sad or neutral faces, the latter two facial expressions, characterised by a low arousal value, producing similar temporal results. As further explained in the general discussion, a high level of arousal speeds up the internal clock

system, meaning that more time units (internal clock ticks) are emitted and time is judged to be longer. Consequently, the perception of angry/ fearful faces, that is assumed to be more highly arousing than the perception of faces expressing other emotions, produce the greatest lengthening effect. In our study, participants were administered a temporal bisection task featuring bodily expressions of fear, happiness and sadness. We thus examined for the first time whether the lengthening effect observed for fearful/angry faces is also observed when people are shown bodily expressions of fear (emotion characterised by high arousal) versus bodily expression of a low-arousal emotion (i.e., sadness). The temporal perception of sad bodily expressions was also compared to that of another high-arousal but positive emotion (i.e., happiness). One can note that neutral stimuli were not used in our study because neutral body expressions by *definition* involve no action tendency. Moreover, as discussed below, in order to consider the underlying mechanisms, we investigated the effects of bodily expressions on temporal bisection judgments for different duration ranges (Experiment 1: 200-800 versus 400-1600 ms; Experiment 2: 200-800 versus 400-1600 versus 600-2400 ms).

EXPERIMENT 1

Method

Participants

Eighty psychology undergraduates (*mean age* = 20.37, SD = 1.37) from Blaise Pascal University, Clermont-Ferrand (France), took part in this experiment in return for course credits. Given that both gender of participants and gender of stimuli are known to influence emotional processes, including bodies' pictures (Kret, Pichon, Grèzes, & de Gelder, 2011b), only females were recruited (i.e., female participants viewing posture of female actors). They all provided their written informed consent to participate in this experiment, which was conducted in accordance with the Declaration of Helsinki.

Material

Participants were tested in a quiet laboratory room, where they were seated in front of a computer. The experiment was controlled by E-Prime software (1.2. Psychology Software Tools, Pittsburg, PA, USA), which also recorded all the data. Participants gave their short and long responses by pressing the corresponding key (D or K) on the computer keyboard. The neutral stimulus was a dark grey circle (diameter 12 cm) displayed in the centre of the computer screen (21 × 17 cm) against a light gray background. The emotional stimuli consisted of the whole bodily expressions of three different emotions: fear, happiness and sadness. For each emotion, we selected the pictures of four female actors (F05, F14, F28 and F30) from the validated database of the bodily expressive action stimulus test (de Gelder & Van den Stock, 2011; see Figure 1). As extensive empirical works show multimodal emotional processing (e.g., de Gelder & Van den Stock, 2011; Scherer & Ellgring, 2007), this dataset consists in face-blurred stimuli in order to only examine body expression language. These pictures were displayed in the centre of the computer screen against the same light grey background as that used for the neutral stimulus.

Procedure

Participants were assigned to 1 of 4 groups (20 participants per group) as a function of stimulus duration (200-800 versus 400-1600 ms) and bodily expression (fear/sadness versus happiness/sadness). In the 200-800-ms condition, the short standard duration (S) was 200 ms and the long standard duration (L) 800 ms. The comparison durations were 200, 300, 400, 500, 600, 700 and 800 ms. In the 400-1600-ms condition, S and L were 400 and 1600 ms, respectively, and the comparison durations 400, 600, 800, 1000, 1200, 1400 and 1600. In each group, the participants performed a bisection task in two phases: training and testing. In the training phase, participants were initially shown the neutral stimulus, once with S and once with L. They then underwent six training trials (three S and three L) to practice responding short or long by



Figure 1. Examples of bodily expressions (fear, sadness, happiness) selected from the validated database of the bodily expressive action stimulus test (de Gelder & Van den Stock, 2011).

pressing the corresponding button. The order of S and L was randomised across these six trials. Each trial started when the participant pressed the space bar after the word "prêt/ready" appeared in the centre of the computer screen, following a random intertrial interval lasting 500-1000 ms. The testing phase, which came immediately afterwards, had the same experimental procedure as the training phase, except for the comparison durations and the stimuli (two different bodily expressions) that had to be timed. As in most bisection studies based on the bisection procedure initially adapted by Wearden (1991) to human adults from the procedure used in animals (Church & Deluty, 1977), each participant completed 10 trials for each stimulus duration, divided into 10 blocks of 14 trials (7 comparison durations \times 2 bodily expressions). The blocks, and the trials within each block, were presented randomly. Each block featured pictures of a single actor. As there were four actors, this made two occurrences of each of the four actors, with one additional occurrence for two other actors randomly selected.

In addition, after the temporal bisection task, the participants assessed the bodily expressions in terms of arousal (from very calm to very excited) and valence (from very unpleasant to very pleasant) on the 9-point Self-assessment Manikin scale (Bradley & Lang, 1994). They also assessed the emotion (happiness, sadness, fear and angry) they saw in the bodily expressions on a 9-point scale from "not at all agree" to "strongly agree". The presentation duration of the bodily expressions was at the mid-point between the short and the long standard duration for each duration condition, i.e., 500 and 1000 ms. In each group, the participants therefore rated eight different emotional stimuli presented in a random order (four actors × two emotions).

Results and discussion

Subjective emotional assessment. For each group (fear/sadness versus happiness/sadness), the responses for the different actors were averaged

and analyses of variance (ANOVAs) were run on emotional assessments with the bodily expression and the duration group as factors. For the fear/ sadness group, the ANOVA¹ on the subjective assessment of the arousal level confirmed a significant main effect of bodily expression (fear: M =3.95, SE = 0.3; sadness: M = 2.68, SE = 0.24, F(1, 1)35) = 26.94, p = .0001, η^2 = .44), indicating that the bodily expression of fear was judged more arousing than that of sadness. The main effect of duration and the duration × bodily expression interaction was not significant (all p > .05). The fearful postures were also judged more pleasant than the sad postures (fear: M = 3.26, SE = 0.23; sadness: M = 2.49, SE = 0.21, F(1, 36) = 19.78, $p = .0001, \eta^2 = .36$), with no effect involving the duration (p > .05). The emotion of fear was also recognised in the bodily expression of fear, F(3,108) = 17.76, p = .0001, η^2 = .33, and the emotion of sadness in the bodily expression of sadness, F(3,108) = 40.20, p = .0001, η^2 = .53, with no significant duration-related effect (p > .05). The participants thus agreed that these postures expressed more the emotion of fear/sadness than another emotion (happiness, sadness/fear and angry; Bonferroni, p < .05). For the happiness/ sadness group, there was also a main effect of bodily expression for the assessment of arousal (happiness: M = 4.34, SE = 0.24; sadness: M =3.28, SE = 0.26, F(1, 36) = 13.70, p = .0001, $\eta^2 =$.28) and valence (happiness: M = 5.72, SE = 0.21; sadness: M = 3.21, SE = 0.18, F(1, 36) = 128.05, $p = .0001, \eta^2 = .78$, with no other significant effects. The participants thus judged more arousing and pleasant the happy than the sad postures. The happiness and the sadness were also clearly identified in the specific bodily expressions [F(3,108) = 53.59, η^2 = .60; F(3, 108) = 29.76, η^2 = .45, respectively, both p = .0001] compared to other

emotions (p < .05), with no effect involving the duration factor.

Temporal performance. Initial ANOVAs were performed on the proportion of long responses, but the results are not reported here because they were similar to those obtained with the bisection point (BP). The BP is the point of subjective equality, that is, the stimulus duration for which participants respond long as often as they do short (percentage of "long" responses = .50). A lower BP value for one stimulus than for another one suggests a lengthening effect, with participants responding long more often for the former than for the latter, even though they are of the same duration. The BPs were derived from the fitting of individual bisection functions with the pseudologistic model (Killeen, Fetterman, & Bizo, 1997). This model fitted our individual data well, with a mean R^2 of .94 (SE = 0.008), no difference in R^2 being found between the experimental conditions (p > .05). The Weber ratio (WR) was also derived from this pseudologistic fit. This is the difference limen (half the difference between the stimulus duration giving rise to 75% "long" responses and that giving rise to 25% "long" responses) divided by the BP. This is a measure of time sensitivity (time variability): The lower the WR, the greater the sensitivity to time. The BP and WR values we obtained are set out in Table 1.

For each of the two emotional groups, we ran an ANOVA on the WR, with bodily expression as the within-participants factor and duration group as the between-participants factor. These ANO-VAs did not yield any significant results (all p >.05). This demonstrated that the scalar properties of the temporal discrimination (constant WR for different duration ranges) were maintained in the different conditions we tested, with the same

¹ For technical reasons, the subjective emotional assessment of some pictures on the 9-point scales was not recorded for a few number of participants: arousal and valence assessment: fear/sadness groups: one participant in the 400/1600-ms condition, one participant in the 600/2400-ms and two participants in the 200/800-ms condition; happiness/sadness groups: one participant in the 400/1600-ms and one in the 600/2400-ms condition; discrete emotion assessment: fear/sadness groups: one participant in the 400/1600-ms, one participant in the 600/2400-ms condition; happiness/sadness groups: two participants in the 400/1200-ms condition.

	200,	/800	400/1600		600/2400	
	Μ	SE	Μ	SE	М	SE
		B	isection point			
Fear/sad bisection			1			
Fear	527	39	938	39	1436	48
Sadness	530	36	996	36	1522	53
Happy/sad bisectio	n					
Happiness	518	39	1038	39	_	_
Sadness	525	36	1057	36	_	_
			Weber ratio			
Fear/sad bisection						
Fear	0.22	0.03	0.18	0.03	0.17	0.03
Sadness	0.22	0.03	0.23	0.03	0.17	0.03
Happy/sad bisectio	n					
Happiness	0.21	0.03	0.17	0.03	_	_
Sadness	0.22	0.03	0.19	0.03	_	_

Table 1. Mean and standard error of bisection point and Weber ratio in the different duration ranges for the bisection tasks with two different bodily expressions: fear versus sadness and happiness versus sadness

sensitivity to time for different bodily expressions and different duration ranges.

For the fear/sadness group, the ANOVA we ran on the BP, using the same factor design as for the WR, revealed a significant main effect of bodily expression, F(1, 38) = 6.45, p = .02, $\eta^2 =$.15, indicating that the BP was lower for bodily expressions of fear than for those of sadness (732 versus 763 ms), consistent with a lengthening effect for fearful versus sad bodily expressions. However, there was also a significant main effect of duration, F(1, 38) = 107.92, p = .0001, $\eta^2 = .74$, as well as a significant duration × bodily expression interaction, F(1, 38) = 5.20, p = .03, $\eta^2 = .12$. This suggests that the lowering of the BP for fearful bodily expressions compared with sad ones was greater in the 400-1600-ms duration group than in the 200–800-ms one (Figure 2). The difference between the BPs for the fearful and sad bodily expressions reached significance in the 400-1600ms group, F(1, 19) = 6.91, p = .02, $\eta^2 = .27$, but not in the 200–800-ms group, F(1, 19) = 0.11, p =.75. In contrast to the fear/sadness group, the ANOVA we ran on the BP for the happiness/ sadness group did not reveal any significant effects [bodily expression, F(1, 38) = 0.98, bodily expression × duration, F(1, 38) = 0.17, both p > .05], except for a significant main effect of duration,



Figure 2. Mean bisection point in the bisection task with two bodily expressions (fear versus sadness and happiness versus sadness) for the 400/1600 and the 200/800-duration conditions.

F(1, 38) = 104.37, p = .001, $\eta^2 = .73$, showing that the BP was higher in the 400–1600-ms duration group than in the 200–800-ms one.

In summary, our results revealed that the perception of fear signals in the bodily expressions was the major source of distortions in time judgment. However, the comparison of BPs between the fearful and sad bodily expressions did not reach significance in the 200-800-ms duration group in contrast to the 400-1600-ms one. This probably stemmed from the duration ranges used in our study, where there were only small differences between the anchor durations. We therefore decided to conduct a second experiment featuring a range of longer durations (600-2400 ms) in the fear/sadness bisection condition to see whether the magnitude of the lengthening effect observed for fear increased with the length of the durations we tested. This longer range of durations had the same ratio as that used in the other bisection tasks Experiment 1 (1:4) in order to keep constant time discrimination difficulty. The anchors durations were thus 3 times and 1.5 times larger than those used in the 200/800-ms and the 400-1600-ms bisection task, respectively, with the same ratio of 1:4 between the two anchor durations. The results obtained with this new duration condition were compared with those obtained with the conditions using shorter durations (200-800 and 400-1600 ms).

EXPERIMENT 2

Method

Participants

Fifty new students (*mean age* = 19.81, SD = 1.78, all females) took part in this experiment in exchange for course credits. As in Experiment 1, they all gave their written informed consent.

Material and procedure

The material and procedure were similar to those used in Experiment 1, with pictures of bodily expressions of fear and sadness. Only the stimulus durations were different, with a short standard duration of 600 ms and a long standard duration of 2400 ms. The comparison durations were 600, 900, 1200, 1500, 1800, 2100 and 2400 ms.

Results and discussion

Subjective emotional assessment. The ANOVA¹ on the affective assessment showed a significant main effect of bodily expression for the arousal level (fear: *M* = 4.08, SE = 0.26; sadness: *M* = 2.95, SE = 0.21, F(1, 48) = 22.32, p = .0001, $\eta^2 = .32$) and the valence (fear: M = 3.47, SE = 0.20; sadness: M = 2.69, SE = 0.19, F(1, 49) = 23.35, p = .0001, η^2 = .32), with no duration and duration × bodily expression effects (p > .05). This confirmed that the fearful bodily expressions were judged not only more arousing, but also more pleasant, that the sadness bodily expression. The emotions expressed in the fearful and sad postures were also recognised among different emotions [F(3, 141) =19.07, η^2 = .29; F(3, 141) = 40.53, $\eta^2 = .46$; p =.0001], with no effect of the duration. Consequently, the postures of fear and those of sadness were judged as representing more the emotion of fear and sadness than another emotion (Bonferroni, p < .05).

Temporal performance. As in Experiment 1, we calculated the BP and WR values by fitting the pseudologistic model to individual data (mean R^2 = .96, SE = 0.009) (see Table 1). An initial ANOVA was run on both the BP and the WR (Table 1), with bodily expression (fear versus sadness) as factor. The ANOVA on the BP showed a significant effect of bodily expressions, F(1, 14) = 6.99, p = .01, $\eta^2 = .34$, indicating that the BP was significantly lower for the bodily expressions of fear than for those of sadness. No effect of bodily expression was found for the WR (p > .05).

Then, a cross-experimental comparison was conducted with an ANOVA on the BP and the WR with the bodily expression as the withinparticipants factor, and the duration group as the between-participants factor [data for the new 600/ 2400-ms duration group (15 participants) were



Figure 3. Mean bisection point for the fearful and the sad bodily expressions in the bisection task for the 3 duration groups: 200/800, 400/1600, 600/2400.

compared with those for the 200-800-ms duration group (20 participants) and the 400-1600-ms duration group (20 participants) studied in Experiment 1]. The ANOVA on the WR did not reveal any significant effect, confirming that the perception of bodily expressions did not disrupt time discrimination, regardless of bodily emotion (all $p_{\rm S} > .05$). The ANOVA on the BP showed a clearly significant main effect of bodily expression, F(1, 52) = 15.25, p = .0001, $\eta^2 = .23$, demonstrating that the BP was lower for bodily expressions of fear than for those of sadness (966.96 versus 1016.02). In addition, there were a significant main effect of duration, F(2, 52) =108.43, p = .0001, $\eta^2 = .81$, and a significant bodily expression × duration interaction, F(2, 52)= 3.73, p = .03, η^2 = .13. As illustrated in Figure 3, this interaction revealed that the magnitude of the difference in BP between the expressions of fear and sadness increased with duration range. The follow-up linear contrast test showed a significant effect of linearity on this interaction, F(2, 52) =3.73, p = .03, $\eta^2 = .13$. In summary, the longer the bisection durations, the greater the lengthening effect when fearful and sad bodily expressions were compared.

GENERAL DISCUSSION

The purpose of this study was to investigate the impact of the perception of bodily expressions of emotion on time perception. It was thus the first study to examine whether the perception of bodily expressions produces temporal distortions consistent with those already observed with other emotional stimuli. Moreover, we used several duration ranges in the temporal bisection task to try and deepen our understanding of the mechanisms involving in emotion-related time distortion.

In Experiment 1, two groups of participants were administered a bisection task in which expressions of happiness (for the first group) and fear (for the second group) were contrasted with expressions of sadness. Results revealed a significant lengthening effect, but only in the fear/sad group, with a significantly lower BP for fearful bodily expressions than for sad ones. This result is entirely consistent with those of previous studies using other kinds of emotional stimuli, including facial expressions (e.g., Bar-Haim et al., 2010; Gil & Droit-Volet, 2011a), emotional scenes (e.g., Angrilli, Cherubini, Pavese, & Manfredini, 1997; Gil & Droit-Volet, 2012; Grondin, Laflamme, & Gontier, 2014; Lui, Penney, & Schirmer, 2011), sounds (e.g., Mella, Conty, & Pouthas, 2011; Noulhiane, Mella, Samson, Ragot, & Pouthas, 2007) and aversive stimuli (e.g., Droit-Volet, Mermillod, Cocenas-Silva, & Gil, 2010; Langer, Wapner, & Werner, 1961). Irrespective of emotional stimulus, these studies have systematically shown that negative high-arousal emotional stimuli are judged to be longer than either negative low-arousal emotion stimuli or neutral stimuli.

As mentioned in the Introduction, for most researchers, this lengthening effect in a threatening context can be explained by the critical role played by arousal in speeding up the internal clock system. According to the models of scalar expectancy theory (SET; Gibbon, 1977; Gibbon, Church, & Meck, 1984), the internal clock is composed of an accumulator, which collects pulses emitted by a pacemaker. Consequently, when the pacemaker rate increases with the increase in arousal, more pulses are collected, and more time is judged to have elapsed. However, a lengthening effect can be explained not only by an arousal-related increase in the pacemaker rate, but also by an increase in the amount of attentional resources allocated to time processing in the case of a faster onset detection for arousing stimuli. When the switch connecting the pacemaker to the accumulator closes earlier, more pulses are transferred to the accumulator and the time is judged to be longer (Zakay & Block, 1996, 1998). SET dissociates these two mechanisms. An attention-based mechanism is assumed to produce an additive effect between emotion and duration, such that the number of pulses accumulated as a result of early switch closure remains constant regardless of duration. By contrast, a pacemakerbased mechanism has a multiplicative effect, with the number of pulses accumulated as a result of the acceleration in the pacemaker rate increasingly proportionally with duration. The testing of the attention (additive effect) and clock-speed (multiplicative effect) hypotheses therefore requires different duration ranges to be examined (Droit-Volet & Meck, 2007). Experiment 2 was specifically conducted to test the predictions of these hypotheses, using a wider range of durations with three different anchor durations in bisection (200-800, 400-1600 and 600-2400 ms). In Experiment 2, the lengthening effect for fearful versus sad bodily expressions increased linearly with duration range, being greater for the long anchor duration (600-2400 ms) than for two the shorter ones (200-800 and 400-1600 ms). Our results were therefore consistent with the hypothesis that fear increases the arousal level which, in turn, speeds up the internal clock system. Consequently, the perception of bodily expressions of fear automatically increases the internal clock rate, as do other highly arousing emotional stimuli. This is consistent with the literature on the emotional body, which describes the processing of threatening bodily expressions as being rapid and automatic, relatively independent of attentional control (van Heijnsbergen et al., 2007). Nevertheless, even if the observed pattern of results provides support for the clock-speed hypothesis, the attention-related hypothesis cannot be dismissed as emotion literature highlights that arousal and attention are closely related (e.g., Vuilleumier, 2005)

The present findings can be also interpreted within the framework of the theory of embodied cognition (Barsalou, 2008) that suggests that the automatic simulation of another person's bodily expression allows observers to feel the other person's emotion and to produce adaptive behavioural responses. Indeed, studies have shown that individuals imitate other people's postures just as they imitate their facial expressions (Magnée, Stekelenburg, Kemner, & de Gelder, 2007). Our results on the effects of bodily expression on the perception of time might thus provide support for the theory of embodiment of time (Droit-Volet, 2014; Droit-Volet & Gil, 2009; Droit-Volet et al., 2013; Schirmer, 2011; Wittmann, 2014). However, bodily expressions of emotion are characterised by motion: avoidance body posture for fearful and sluggishness for sadness. Several studies have reported the same time dilation as that observed in our study when people are exposed to nonemotional bodily motion presented either statically (posture resulting from motion) or dynamically (Nather, Bueno, Bigand, & Droit-Volet, 2011; Orgs, Bestmann, Schuur, & Haggard, 2011; Sgouraini & Agiro, 2014; Wittmann, Van Wassenhove, Craig, & Paulus, 2010). Recently, Zhang, Jia, and Ren (2014) even observed that the duration of words and expressions associated with rapid movements (e.g., gallop, run like the wind) was overestimated compared with those associated with slow movements (sluggish, limp). The speed of motion involved in bodily expressions is therefore likely to play a critical role in time distortions. Fleeing in response to a threat is necessarily faster than remaining prostrate, overwhelmed by sadness. The distortion of time with bodily expressions can therefore be indirectly linked to the dynamics of emotional action. For a long time now, the subjective experience of time has been associated with dynamic movements in space (Piaget, 1946).

Although speculative at this point, findings of Experiment 1 allow us partially to disentangle what results from motion (i.e., the perceptive shape of postures) and what results from emotion (i.e., the emotional action tendency). Indeed, compared with the postures of sadness, those of happiness and fear were relatively similar, with marked bodily motion and arms raised in every posture (Figure 1). However, unlike the comparison between bodily expressions of fear and sadness, the comparison between bodily expressions of happiness and sadness failed to reach significance in temporal bisection judgment. Consequently, it seems that it was not so much the shape of the posture but the emotion expressed in the whole body that affected participants' time judgements. This provides additional confirmation of studies of the emotional body pointing out a processing of the actual emotion expressed by the body (de Gelder & Hortensius, 2014). Indeed, the perception of bodily expressions of fear activates not only the motor areas involved in the perception of human motion (i.e., superior temporal sulcus), but also the amydala involved in the processing of threatening situations (Grèzes, Pichon, & de Gelder, 2007; Hadjikhani & de Gelder, 2003; Kret, Pichon, Grèzes, & de Gelder, 2011a). Finally, regarding possible limitations of our study, the limited number of emotions investigated, the cross-experimental comparisons in timing performance, and the exclusive female population, may be considered. Further experiments are therefore required to identify the role of speed of motion in the effect of emotional body postures on time perception.

Our study on emotional bodily expressions opens up a new avenue of research on the role of action in the perception of time. First, however, we must investigate whether or not bodily expressions produce similar time distortions to facial expressions. As reported in the Introduction, recent studies have shown that bodily and facial expressions of emotions share the same characteristics (de Gelder et al., 2004; Reed, Stone, Bozova, & Tanaka, 2003; van Heijnsbergen et al., 2007). However, despite these similarities, the authors also assume that bodily expressions are more primary expressions of emotion, in that they are much older from a phylogenetic evolutionary perspective than emotional faces and can be recognised from a greater distance than faces. Taken as a whole, these studies suggest that emotions expressed by the body are more arousing than

emotions expressed by the face, because of the fundamental nature of the former, where the motion of emotion is added to the meaning of emotion (i.e., action readiness). Consequently, the speed the internal clock may be greater for the perception of bodily expressions of fear than for the perception of fearful facial expressions. This issue will have to be addressed in future research.

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Passage of time judgments are not duration judgments: Evidence from a study using Experience Sampling Methodology

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Author contribution statement

Conceived and designed the experiments: SDV & JW Performed the experiments: SDV Analyzed the data: SDV & JW Contributed reagents/materials/analysis tools: SDV Wrote the paper: SDV & JW

Keywords

time, Time Perception, Passage of time, Experience sampling methodology, Elderly

Abstract

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This study examined relations between passage of time judgments and duration judgments in everyday life, in young and elderly people, with an Experience Sampling Method (ESM). The duration judgments were assessed by verbal estimation and interval production measures. The results showed no difference between young and elderly people in judgments of rate of passage of time, a result contrary to the conventional idea that time passes more quickly as we get older. There were also no significant relation between the judgment of passage of time and the judgments of durations. In addition, the significant predictors of individual differences in the judgment of passage of time (emotion states and focus of attention on the current activity) were not predictors of judgment of durations. In sum, passage of time judgments are not related to duration judgments.

Ethics statement

(Authors are required to state the ethical considerations of their study in the manuscript including for cases where the study was exempt from ethical approval procedures.)

Did the study presented in the manuscript involve human or animal subjects: Yes

Please state the full name of the ethics committee that approved the study. If the study was exempt from this requirement please state the reason below.

The Sud-Est VI Statutory Ethics committee

Please detail the consent procedure used for human participants or for animal owners. If not applicable, please state this. All participants signed a consent form approved by the Sud-Est VI Statutory Ethics committee, and received 40 euros for their participation.

Please detail any additional considerations of the study in cases where vulnerable populations were involved, for example minors, persons with disabilities or endangered animal species. If not applicable, please state this. This is not applicable

Passage of time judgments are not duration judgments: Evidence from a study using Experience Sampling Methodology

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Abstract

This study examined relations between passage of time judgments and duration judgments in everyday life, in young and elderly people, with an Experience Sampling Method (ESM). The duration judgments were assessed by verbal estimation and interval production measures. The results showed no difference between young and elderly people in judgments of rate of passage of time, a result contrary to the conventional idea that time passes more quickly as we get older. There were also no significant relation between the judgment of passage of time and the judgments of durations. In addition, the significant predictors of individual differences in the judgment of passage of time (emotion states and focus of attention on the current activity) were not predictors of judgment of durations. In sum, passage of time judgments are not related to duration judgments.

1. Introduction

The main aim of the work reported in this article is to explore relations between passage of time judgments (PoTJs) and duration judgments (DJs), with the latter being assessed by verbal estimation and interval production measures. In addition, the present study provides a partial replication of Droit-Volet and Wearden's (2015) recent work on a comparison of passage of time judgments in a student-age group and a group of elderly people, around 50 years older.

A PoTJ is a judgment about how fast time seems to pass in some situation. It is generally measured with a question such as "How fast does time pass for you?" or "How did time pass relative to clock time?", with responses usually being given on a Likert-type scale with 7 points from "very slowly" to "very fast" (e.g. Blewett, 1992; Friedman and Janssen, 2010; Wittman and Lehnhoff, 2005). Studies using this type of question have suggested that subjective experience of passage of time changes as a function of health status of individuals or contexts (for a review see Droit-Volet, 2013). For example, depressed people experience a slowing down of time passage, such that "time seems to drag. A day feels like a year" (Ratcliff, 2012).

Some authors assume that this experience of time passage reflects fundamental changes in basic mechanisms underlying the representation of duration, for example, in the rate of the pacemaker of some sort of internal clock (Rammsayer, 1990). According to the popular

Scalar Expectancy Theory, the judgment of durations depends on the number of pulses emitted by a pacemaker and counted in an accumulator (Gibbon, 1977; Gibbon et al., 1984). Consequently, if there is a slowdown of the internal clock rate in patients suffering from depression, they would introspectively feel this change, and would express it in terms of slowing down of the passage of time. However, as discussed later, in human beings, the consciousness of time passing faster or slower than usual cannot be simply dependent on number of pulses counted during an event. In line with this idea, a significant number of studies suggested that patients with depression do not show deficits in their abilities to judge stimulus durations, even though they experience time passing slowly (for a recent meta-analysis see Thönes and Oberfeld, 2015).

The principal question addressed here concerns this relation between PoTJs and judgments of duration. One way of addressing this issue might be to take concurrent measurements of both the judgment of durations and the judgment of passage of time and examine how the two measures covaried. A small number of studies have examined the relation between the retrospective judgment of durations (when the people were not alerted in advance that a question about time would be asked) and the judgment of the rate of passage of time. When participants were asked about PoTJs and duration judgments after an action film or a relaxation video, Wearden (2005) did not find any relationship between these two forms of judgment. In fact, people judged that time was passing more quickly for the action film than for the relaxation film, while the action film was retrospective time judgments of three durations of a film under two processing conditions. In one of these, the instruction was simply to watch the film and in the other people were required to count each time one of the characters had spoken after another character. The different conditions changed PoTJs, but duration judgments were unaffected.

However, the lack of relationship between the DJs and PoTJs in these studies might be related to the fact that, in the retrospective timing tasks used, the participant's attention is not focused on the processing of time. In addition, the PoTJ and the DJ are measured from a single time interval, or a few time intervals, ranging from a few tens of seconds to minutes. Also, the PoTJ of an event created in laboratory may differ from PoTJs in everyday life which may involve longer periods of time. Lamotte et al. (2014) showed that individuals are not aware of most of the factors that influence their perception of durations in the range from milliseconds to seconds. They are only aware of fluctuations of passage of time in two contexts those when, introspectively, they feel themselves happy or sad and engaged in a daily activity. In a recent study assessing PoTJs in everyday life with the technique of Experience Sampling Methodology (ESM), Droit-Volet and Wearden (2015) found that PoTJs in everyday life changed with the individuals' moods and their degree of immersion in the activity they were currently engaged in. Consequently, we decided to use the ESM method to examine the relation, if any, between prospective judgment of durations and the lived experience of passage of time, when the individuals are aware of their states of happiness and the intensity of their engagement in activity.

The ESM method (see Connor et al., 2003) is an ecological approach that is mainly used in clinical psychology but has been used in the domain of time psychology in a few studies (Conti, 2001; Larson and von Eye, 2006; Droit-Volet and Wearden, 2015). Conti (2001) examined the link between PoTJs and intrinsic or extrinsic work motivation, and Larson and von Eye (2006) the link between this time judgment and the degree of engagement in activities. Droit-Volet and Wearden (2015) studied differences in PoTJs in young and elderly people. In all these ESM studies, the participants received "alerts", at quasi-random times, several times per day (8 or 10). When an alert is received, the participant's task is to respond

to a short questionnaire, with the aim being to collect immediate impressions, rather than those based on reflection. For example, Droit-Volet and Wearden (2015) assessed PoTJs in young and elderly people at the time of the alert, as well as the rating of their emotional states (happiness, sadness, arousal, relaxation), and their level of occupation (the difficulty of the activity performed at the time of the alert – Activity difficulty -, and the focus of attention on that activity – Attention capture -).

In the present ESM study, we thus assessed PoTJs, as well as people's emotional states and the intensity of their activity, but we also measured duration judgments using a verbal estimation task, and an interval production task. This enabled us not only to relate PoTJs at the time of the alerts to duration judgments, but also enabled us to explore potential predictors of both PoTJs and duration judgments. In addition, following Droit-Volet and Wearden (2015) we used two participant groups, one of young people and the other of elderly persons.

2. Materials and method

2.1 Participants

The final sample was composed of 27 participants (18 women and 9 men): 14 students at University Clermont Auvergne (mean age = 20.50, SD = 1.99, age range from 18.88 to 22.42) and 13 elderly people (mean age = 69.46, SD = 3.62, age range from 68.01 to 71.42). Three additional individuals (1 young and 2 elderly adults) participated in the study but stopped the experiment, so their data were not included in the final sample. All participants signed a consent form approved by the Sud-Est VI Statutory Ethics committee, and received 40 euros for their participation. The Mini Mental State Examination (MMSE) was administered to elderly people to reject those suffering from dementia (mean score = 29.54, SD = 0.66). The IQ scores on the Weschsler Adult Intelligence Scale (WAIS-III, Grégoire and Wierzbicki, 2009) were also measured but they did not differ significantly between the young (M = 98.28, SD = 10.70) and the older participants (M = 105.69, SD = 11.70), t(25) = -1.72, p = .10. Their depression scores on the Beck Depression Inventory (BDI) test (Beck et al., 1961) were also similar (3.64 vs. 3.23, t(25) = 0.29, p = .78).

2.2 Apparatus

Motorola G Android Jelly Bean smartphones were used for this experiment with data collection programs specifically written by the CATech (http://lapsco.univ-bpclermont.fr/catech) of the Laboratory of Social and Cognitive Psychology of the University Clermont Auvergne. The programs delivered and recorded all experimental events (alerts, questions and temporal tasks). The participants responded by pressing on the touch screen of the smartphone. The stimulus used in the verbal estimation and the temporal production task was a sound (La, 440 hz).

2.3 Procedure

Participants initially received an explanation of the procedure of the experiment and the functioning of the smartphone (with one demonstration), then filled in the different scales (MMSE; WAIS-III, BDI). They then kept their smartphone for 5 consecutive weekdays, from Monday to Friday. They received 8 alerts per day, from 8.00 a.m. to 8.00 p.m., with one alert randomly delivered within each 90-min period, with at least 15 minutes between any two alerts. This made a total of 40 alerts per participants.

After each alert, the participant performed the verbal estimation task and the production task following by their PoTJ. For the verbal estimation task, the participant was required to judge (using a scale ranging between 100 and 2000 ms) three different durations, each randomly chosen between (1) 350 and 650 ms, (2) 850 and 1150 ms, and (3) 1350 and 1650 ms, respectively. The presentation order of these 3 durations was random. For the production task, the participants were initially presented with a duration value: 500, 1000 or 1500 ms. A blue circle then appeared and the participants were required to press on the circle to trigger a sound, then release the pressure, thus stopping the sound, when they judged that the sound duration equalled the value indicated. The duration presentation order was also random. For all temporal tasks, the participant initiated a trial by touching the screen after the word "ready', and this was followed after 500 ms by the events of the trial. Furthermore, the participant did not receive feedback regarding their performance on the verbal estimations and time productions.

After the temporal tasks had been performed, the question "At the moment, the moment of the alert, how does time pass for you compared to the time of the clock" was given. The participant responded on a 7-point scale: "(1) much slower – (2) moderately slower – (3) a little slower – (4) at the same rate than the clock - (5) a little faster - (6) moderately faster - (7) much faster". Following this PoTJ question, they responded to affective and activity questions. There were 4 affective questions : "At the moment of the alert, do you feel (1) happy" (Happiness), (2) "sad" (Sadness), "excited/stimulated" (Arousal) and "relaxed/calm" (Relaxation). The activity questions concerned the difficulty of the activity performed at the moment of the alert (Activity difficulty) and whether it captured the participants' attention (Attention capture). For these different questions, participants responded on 7-point scale from "not at all" to a "lot".

3. Results

For the ESM phase of our study, the overall average percentage of missed alerts for the 40 alerts (8 alerts X 5 days) was 5 (M = 5, SD = 5.50), min = 0, max = 20%) with no difference between the young and elderly participants on average (4.82 vs. 5.19, t(25) = .17, p = .87). Consequently, anybody was excluded on the basis of their ESM scores. The responses for the different variables at the times of the alerts were analyzed by multi-level modelling, using SPSS. The multi-level modelling procedure is a variant of regression, which generates an estimate (coefficient) indicating whether the outcome variable and its predictor are positively related (with a positive coefficient) or negatively related (with a negative coefficient). The coefficient essentially represents how much the outcome variable changes for an unit change in the predictor. The significance of the relation between the variables is indicated by the significance of the predictor, assessed by a *t*-value. However, the values of the coefficients are not meaningful when the predictor variables are arbitrarily encoded, as for our betweengroup analysis. It is also important to recall that multi-level modelling is a type of repeatedmeasures design, and so is generally considered more powerful than a simple between-groups design (Bolger et al., 2012), especially when many observations per participant are collected for each variable measured (e.g., usually 40 in our study). Calculation of statistical power for multi-level designs is not, however, straightforward and disagreement exists as to the best method (Bolger et al., 2012; see also Nezlek, 2012).

Table 1 shows means and standard errors of scores on the different variables tested in our study for the young and older groups. The *t*-values indicated the between-group differences on these variables. There were no significant between-group differences for the verbal estimates (all p > .05). A significant between-group difference was only observed for the temporal production of the shortest duration of 500-ms (p = .02). As shown in Figure 1,

durations produced were shorter for the elderly group than for the young people when they had to produce the target duration of 500 ms. The between-group difference did not reach significance for two longer target durations. Additional analyses were performed with the day and the time of alert introduced into the model. These analyses showed no variation either in the verbal estimates or the durations produced with the time of the alert (verbal estimates: 500-ms, t(73.89) = .41; 1000-ms, t(65.45) = .53; 1500-ms, t(68.04) = 1.04; Production: 500ms, t(34.24) = 1.16; 1000-ms, t(36.71) = .38; 1500-ms, t(36.41) = .37, all p > .05). There was nevertheless a significant link between day and the verbal estimates for all stimulus durations (500-ms, t(130.47) = -4.10; 1000-ms, t(102.10) = -4.96; 1500-ms, t(78.49) = -3.82, all p =.0001), and the production of the different target durations (500-ms, t(35.45) = 3.16; 1000ms, t(37.91) = 4.80; 1500-ms, t(35.60) = 4.96, all p < .001). When we used a composite measure for the verbal estimates (mean of estimates for the 3 stimulus durations), the difference in verbal estimates reached significance between the first (1298.51) and the 3 last days (1078.77, 1025.11, and 996.25, respectively), and the second (1178.40) and two last days (Bonferroni, p < .05), with no difference between the two first days (p > .05). That is, the length of verbal estimates decreased over days. Conversely, for the temporal productions, the values of reproduced durations increased from the first to the third days (Bonferroni, p < p.05) after which the time produced no longer changed (p > .05).

There was no significant difference between the young and elderly people in the judgment of the rate of passage of time (p > .05). Additional analyses also obtained no significant differences on this measure with respect to the day (t(34.69) = .90, p = .38) and the alert time (t(33.08) = .17, p = .87). Responses were also similar in the two groups for emotion-related questions and the difficulty of activity performed at the time of the alert (p > .05). The extent to which the activity at the time of the alert captured the participant's attention was however significantly lower for the old than the younger group (p = .02).

We next analyzed some potential predictors of PoTJs (shown in Table 2). First, we used two composite measures of duration judgments. These were the mean of verbal estimates for the 3 stimulus durations, and the mean time produced for the 3 target durations. The mean time produced for the 500-ms duration was also included, as there was a significance difference between the young and the older group. In neither participant group was either measure of timing predictive of PoTJs. In other words, the verbal estimation and the production of durations did not vary with the experience of time passage at the moment of the alert (all p > .05).

In contrast to the dissociation between PoTJs and measures of duration judgments, many variables measured at the time of the alert were predictive of PoTJs. Positive affect was significantly positively related to PoTJs for both the young and older groups (p < .05). Indeed, for both young and elderly people, the passage of time was judged to go faster when happiness increased. Similarly, negative affect was significantly negatively related to PoTJs in both groups such that the time was judged to pass slower when the state of sadness increased. Reported arousal was also positively related to PoTJs and reported relaxation negatively related, but only for the young group. There was no significant effect of this arousal variable in the older participants. In addition, the extent to which the activity captured attention at the moment of the alert was positively and significantly related to PoTJs for both the young and the older groups, while no significance was found for the judgment of the difficulty of the activity for both groups.

We next used the variables listed in Table 2 from happiness to attention capture to try predict verbal estimates (Table 3) and the times produced (Table 4) for the young and older participants taken separately. This made a total of 24 analyses (6 predictors x two timing

measures x two groups). Of these 24, only one was significant at 0.05, and this was the "attention capture" for the younger group, such that the more their attention was focused on the activity that they performed at the time of the alert, the shorter their temporal estimates. As indicated Table 3, there is obviously a significant relationship between verbal estimates and time produced: the longer estimates in the verbal estimation task, the shorter the time produced in the temporal production task.

4. Discussion

The results of our study replicated those found by Droit-Volet and Wearden (2015) by demonstrating that PoTJs did not significantly differ between young and elderly people, a result contrary to the conventional idea that time passes more quickly as we get older. Our results confirmed that the experience of time passage in the everyday life did not fluctuate with age but, rather, with the individual's emotion states. When the participants felt happy, they reported higher rate of time passage. Conversely, when they felt sad, time seemed to drag. In addition, our results suggested that the young and older individuals experienced an acceleration of time passage with the increase in the focus of attention on the current activity. Droit-Volet and Wearden (2015) only found this result for young people, possibly related to the great variability in activities performed by elderly people compared to young people who were all students. However, we found a positive relation between PoTJ and attention capture by the activity performed at the moment of the alert, whereas Droit-Volet and Wearden found a negative relation. The translation of effect of attention capture by the activity in terms of passage of time thus seems more inconsistent in individuals than emotional effects. Nevertheless, whatever orientation in the speed of time passage (speeding up or slowing down), our study, like that conducted by Droit-Volet and Wearden (2015), demonstrated that emotion and attention are the two main factors at the origin of fluctuations of subjective experience of time passage.

The original contribution of the present study is that it also tested judgment of durations at the same time as the participants reported their experience of time passage. The results found no significant relation, or any relation approaching significance, between these two forms of time judgment. Neither the verbal estimates nor the times produced in the temporal production task covaried significantly with the PoTJs. It seems therefore that the subjective feeling that time passes more quickly or slowly than the normal rate of external clocks does not depend on the number of pulses accumulated by a potential internal clock that might provide the raw material for the representation of durations. The duration perceived can change with the acceleration of the internal clock mechanism (for a review see Droit-Volet et al., 2013), without people feeling that time passes more quickly. Conversely, participants may feel that the time passes more quickly without modification in the rhythm of internal mechanism which forms the basis of the perception of duration. This is entirely consistent with the studies on patients with depression which have shown that they express a slowing down of time passage, although they do not exhibit any deficit in the time perception compared to healthy people (Thönes and Oberfeld, 2015), as well as data from the few earlier studies which collected PoTJs and restrospective duration judgments from the same experiment (e.g. Wearden, 2005, 2008).

Our study using ESM therefore shows a dissociation between the judgments of durations and the judgments of passage of time. This dissociation clearly appears in our findings showing that the factors that predicted the individual differences in PoTJ were not significant predictors of judgments of durations both for the verbal estimation and the reproduction task. Indeed, in contrast to the PoTJs, judgments of durations did not vary with the state of happiness or sadness felt at the moment of the alert. Only the factor related to attention paid

to the current activity affected these two different forms of time judgment. However, the relation was in the opposite direction for the two types of judgment: the speed of passage of time increased with increasing attention capture while the verbal estimated decreased. Consequently, our results on the prospective time judgments confirmed those found with retrospective time judgments that suggested no evidence that PoTJs and DJs are related (Wearden, 2005, 2008: Wearden et al., 2014).

Other studies need to be conducted before we can definitely confirm the absence of a link between PoTJs and judgments of durations. However, the lack of relation between these two forms of judgment supports the idea that in human beings there are several different types of time judgments. The first one is a judgment of durations common to human beings and to other animals that involves a basic cerebral system functioning as an internal clock. A second is a judgment of passage of time specific to human beings. What determines the subjective experience of a speeding up or a slowing down of the flow of time is still not known for certain, with only a small amount of research to date (e.g. see Droit-Volet & Wearden, 2015; Flaherty, 1993; Lamotte et al., 2014) Larson, 2004; Larson and von Eye, 2006; Wearden, in press). However, phenomenologists (e.g., Husserl, 1964; Minchowski, 1968/1988) have considered for many years that the judgment of time passage results from individuals' introspection on their internal life, a "time of self" compared to a "time of world" (Minchowski, 1968/1988) (for a review see Droit-Volet, in press). The challenge is to scientifically examine this form of time judgment and its impact, if any, on other types of time judgment. Our study provides an initial response to this difficult question: concluding that there is no direct link.

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Figure Captions.

Figure 1. Mean verbal estimates (upper panel) and mean time produced (bottom panel) plotted against stimulus duration in young and elderly people.



Table 1. Means and standard errors of measures of duration judgments from the verbal estimation and production tasks, scores on the passage of time judgments, and the other measures assessed by the ESM procedure. Data are shown separately for the young and older groups.

Variable	Mean	St. Error	<i>t</i> value	<i>p</i> value
500-ms Ve	rbal estima	ntion		
Young	589.58	55.76	0.51	.62
Older	548.88	57.83		
1000-ms V	erbal estim	nation		
Young	1135.64	77.29	0.25	.80
Older	1107.46	80.17		
1500-ms V	erbal estim	nation		
Young	1646.10	89.90	0.14	.89
Older	1627.75	93.25		
500-ms Pro	oduction			
Young	573.60	45.68	2.58	.02
Older	403.94	47.39		
1000-ms P	roduction			
Young	898.63	58.77	1.72	.10
Older	753.11	60.98		
1500-ms P	roduction			
Young	1171.38	79.34	1.17	.25
Older	1044.27	82.33		
Passage of	Time Jude	gment		
Young	4.75	.20	.90	.38
Older	4.49	.20		
Happiness				
Young	4.78	.17	.95	.35
Older	5.01	.18		
Sadness				
Young	2.29	.27	.11	.91
Older	2.25	.28		
Arousal				
Young	4.32	.24	.91	.37
Old	4.01	.25	-	
Relaxation				
Young	3 38	27	31	76
Older	3 50	28		
Activity Di	fficulty	.=0		
Young	3 06	28	1 55	13
Older	2 44	20	1.55	.1.
Attention (² .77 <i>anture</i>	.29		
Young	4 69	22	2 44	02
Older	3 92	23	<i>≌</i> , г⊤	.02

Table 2. Potential predictors of passage of time judgments. The predictor is shown along with its associated coefficient value [confidence interval], *t*- and *p*-value. The timing measure predictors are shown with higher precision than the others as with 2 decimal places they would all be rounded to zero. Data are shown separately for the young and older group.

Predictor	Estimate	St. Error	t value	p value
Verbal esti	mation			
Young	0.00004 [0005, .001]	.0002	.20	.85
Older	0001 [0006, .0004]	.0002	46	.68
Production	n – – –			
Young	.0002 [0005, .0009]	.0004	.61	.55
Older	00001 [0004,.0004]	.0002	05	.96
500-ms Pr	oduction			
Young	.0002 [0007, .001]	.0005	.52	.60
Older	0002 [0007,.0004]	.0003	68	.50
Happiness				
Young	.28 [.17, .39]	.06	5.06	.0001
Older	.12 [007, .23]	.06	1.94	.05
Sadness				
Young	23 [35,11]	.06	-4.16	.001
Older	13 [22,04]	.05	-2.93	.004
Arousal				
Young	.21 [.10, .32]	.05	3.97	.0001
Older	.02 [08, .13]	.05	.44	.66
Relaxation				
Young	19 [27,11]	.04	-4.92	.0001
Older	003 [09, .085]	.04	08	.94
Activity Dį	fficulty			
Young	04 [16, .08]	.06	67	.52
Older	.07 [007, .15]	.04	1.96	.07
Attention (Capture			
Young	.10 [.02, .18]	.04	2.49	.02
Older	.08 [.006, .16]	.04	2.28	.03

Predictor	Estimate	St. Error	t value	<i>p</i> value				
Production	1							
Young	-0.64 [81,47]	.08	-7.73	.0001				
Older	-0.63 [84,43]	.10	-6.18	.0001				
Happiness								
Young	-1.99 [27, .23]	13.17	15	.88				
Older	-54.11 [-116, 8.24]	31.56	-1.71	.09				
Sadness								
Young	-7.05 [-33.05, 18]	13.24	53	.59				
Older	-13.42 [-21, 33]	30.69	44	.67				
Arousal								
Young	6.04 [-21, 33]	12.46	.49	.64				
Older	-21.70 [-64, 21]	21.84	99	.32				
Relaxation								
Young	.11 [-18, 18]	9.46	.01	.99				
Older	-26.81 [-66, 12]	20.01	-1.34	.18				
Activity Difficulty								
Young	1.37 [-13, 16]	7.50	.18	.85				
Older	26.88 [-17, 70]	21.41	1.26	.22				
Attention (Capture							
Young	16.20 [-32,13]	7.68	-2.11	.05				
Older	21.37 [-16, 59]	18.91	1.13	.26				
Predictor	Estimate	St. Error	<i>t</i> value	<i>p</i> value				
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Happiness								
Young	54 [-17, 15]	7.67	07	.94				
Older	34.47 [-4, 73]	18.29	1.88	.08				
Sadness								
Young	-2.72 [-25, 19]	10.02	27	.79				
Older	.63 [-37, 38]	17.48	.04	.97				
Arousal								
Young	6.24 [-8, 21]	6.79	.92	.38				
Older	16.76 [-5, 39]	10.33	1.62	.13				
Relaxation								
Young	-2.75 [-18, 13]	6.55	42	.69				
Older	-3.83 [-29, 22]	11.99	32	.76				
Activity Difficulty								
Young	2.48 [-5, 10]	4.17	.60	.55				
Older	4.04 [-9, 18]	7.12	.57	.57				
Attention (Capture							
Young	9.22 [-2, 20]	5.30	1.73	.11				
Older	-11.42 [-28, 5]	8.10	-1.41	.18				

Table 4. Potential predictors of performance on the interval production task. For each group, the predictor is shown along with its associated coefficient value [confidence interval], *t- and p-value*.



Manuscript "Temporal Context Influences the Perceived Duration of Everyday Actions"

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1.1 Abstract

Accurate timing is a key factor contributing to performance in every cognitive task. However, in most of the traditional research on time perception simple stimuli and artificial tasks are used. More precisely, cues that mark a to-be-timed interval generally have clear and sharp on- and offsets. These circumstances make generalizations to more complex stimuli used in other cognitive tasks or encountered in our everyday life extremely difficult. Here we show that findings of traditional timing tasks can be replicated in more real-world like experimental settings. Short video clips showing a stick-figure performing different everyday actions (e.g., mixing batter in a bowl) were presented. Participants were asked to reproduce the duration of the action seen in the video-clip. Our data is in conformity with traditional findings. First, timing sensitivity remained constant as the action durations varied, as predicted by the scalar property of time perception. Second, previously encountered action durations influenced the perceived duration of a current action, a phenomenon known as temporal context effect. Taken together, we show that findings from artificial laboratory studies can be generalized to more complex environments.

Keywords: time perception, real-world tasks,

1.2 Introduction

Timing and the perception of time is a fundamental aspect of our daily life. Anything we perceive and experience we perceive and experience over time, and performance in any activity or task we engage in is highly dependent on precise timing. Traditional research on time perception involves estimation, comparison, or reproduction of an interval marked by the appearance and dis- or reappearance of simple and static stimuli. The on- and offset of the interval to be timed are clearly and sharply defined, leaving no ambiguity about the exact startand endpoint. Critically, events in the real world often lack sharp and salient onand offsets, and intervals are usually embedded in a larger context. As a consequence, experimental tasks in traditional laboratory studies become highly artificial and it is as of yet unclear in how far those well-studied findings generalize to more complex environments (Matthews & Meck, 2014; van Rijn, 2014).

One common effect found in these traditional laboratory studies is the scalar property of time perception (Allman, Teki, Griffiths & Meck, 2014; Wearden & Lejeune, 2008; for an extensive review see Grondin, 2014). The scalar property is a form of Weber's law, stating that the standard deviation is proportional to the duration to be timed. Consequently, timing sensitivity follows Weber's law in that relative sensitivity is preserved for varying interval durations.

Another well documented phenomenon is the effect of context on interval timing, first captured in Vierordt's law. In short, Vierordt's law describes the central tendency effect: when confronted with varying interval durations, participants tend to overestimate short durations and underestimate long durations (Lejeune & Wearden, 2009). By manipulating the temporal context, Jazayeri and Shadlen (2010) showed that participants under- or over-reproduced the duration of the same interval depending on temporal context. Contexts effects have been investigated by taking into account N-1 (read as N minus one) effects, i.e., the effect of the duration of the previous trial on the current trial (Gu & Meck, 2011; Taatgen & van Rijn, 2011), by trial-by-trial updating of an internal reference model (Bausenhart, Dyjas & Ulrich, 2014; Dyjas, Bausenhart & Ulrich, 2012) and by comparisons to Bayesian integration models (Acerbi, Wolpert & Vijayakumar, 2012; Jazayeri & Shadlen, 2010; for a review, see Shi, Church & Meck, 2013).

As already mentioned, these findings have been well studied by using simple and static stimuli. To overcome staticness of artificial stimuli, researchers have started to use more dynamic stimuli (e.g., moving or rotating geometrical shapes) in their experiments (Matthews, 2011; Sasaki, Yamamoto & Miura, 2013). Common findings in interval perception studies using dynamic stimuli are i) moving stimuli seem to last longer than static ones, and ii) apparent duration increases with increasing stimulus speed, a phenomenon known as subjective dilation (Eagleman, 2008; van Rijn, 2014).

With a "real-world" experimental setup van Rijn (2014) tested the effect of speed of driving on time perception. Video snippets from a recording of a driving simulator session served as stimuli (recordings were made from the driver's perspective). The snippets were shown at either original, faster or slower speed and participants had to categorize the duration of the videos as shorter or longer than a previously learned duration. The data exhibited the same subjective dilation effects previously found (Eagleman, 2008), i.e., perceived duration increased with increasing stimulus or driving speed. Importantly, previous findings on subjective dilation were generalized not only to real-world-like settings, but also to timing from a first-person perspective.

Perspective is an important aspect of being in the real world. Everything we perceive, and thus also time, is perceived from first-person perspective. With simple stimuli the effect of perspective cannot be tested because there is no change in perspective possible. Therefore, the effect of perspective on time perceptions is as of yet unknown. However, it has been shown that perceived or imagined distance affects time perception, in that events that happen further away from the observer seem to last longer (Gorea & Hau, 2013; Wiener &

Thompson, 2015; Zäch & Brugger, 2008). One could argue that manipulating perspective is in a way manipulating perceived distance, because objects are generally closer to oneself from first-person perspective. In another line of research it has been shown that a feeling of personal authorship for an event reduces the perceived interval between cause (i.e., one's action) and effect (Ebert & Wegner, 2010). Although it can be argued that perceiving a scene from a first-person perspective does not imply authorship per se, it is an important factor to induce a feeling of authorship.

In everyday life, we are not only timing the behavior of static or moving objects or abstract shapes, but we are also timing human-object- or human-humaninteractions. Studies testing differences in time perception between animate and inanimate figures showed that animacy affects time perception (Carrozzo & Lacquaniti, 2013; Carrozzo, Moscatelli & Lacquaniti, 2010; Moscatelli, Polito & Lacquaniti, 2011; Orgs, Bestmann, Schuur & Haggard, 2011). It has been proposed that there are different mechanisms at work when timing biological motion (animate stimuli) on the one hand, and visual motion (inanimate stimuli) on the other hand (Lacquaniti et al., 2014). This highlights the importance to study time perception in naturalistic contexts, including human motion and (inter-) action.

In the current study, we aimed to investigate interval perception in real-world settings. Specifically, we asked whether common effects found in traditional laboratory studies, scalar property and context effects, can be generalized to timing in real-world settings. Furthermore, we aimed to explore possible effects of perspective on time perception. To this end, participants were asked to reproduce the duration of an action they had previously seen in a video. The videos showed a stick figure performing six different everyday actions filmed from first- or third-person perspective (for an example, see Figure 1). For each action, there was a longer and a shorter version. Importantly, actions showed in shorter videos were not necessarily performed faster (e.g., drinking fast), but showed an action being performed at normal speed over a shorter timespan.

To be able to compare the reproduced durations to objective durations, we used durations computed by an algorithm (Semantic Event Chain (SEC) extraction) used in AI and robotics to decompose actions or action sequences into atomic (sub-) actions (Aksoy & Wörgötter, submitted). During SEC extraction videos are examined and segmented according to spatiotemporal hand-object relations. The pure action according to this algorithm lasts from the first contact with the object involved in a certain action until letting go of that object. In an additional experiment (see Supplemental Material), we were able to show that when asked to segment a video showing an action in such a way that only the pure action is captured in the new segment, participants and the SEC algorithm produce very similar action durations.

1.3 Materials and Methods

1.3.1 Participants

Twenty-three psychology students (mean age: 19.3 years, range: 18-22 years, 17 female) participated in the experiment and received partial course credit. All

participants had normal or corrected-to-normal vision. Informed consent as approved by the Psychology Ethical Committee of the University of Groningen (15008-NE) was obtained before testing.

1.3.2 Stimuli

Videos of a human actor wearing a motion capture suit and performing six different actions (drinking, mixing, pouring, putting on and taking down) were recorded from third- and first-person perspective. The action were *drink* (figure drinks from a cup), *mix* (figure uses a whisk to mix something in a bowl), *pour* (figure pours a liquid into a cup), *put on* (figure picks up a bowl and puts it on a cubical object), *take down* (figure picks up a bowl placed on a cubical object and puts it down on the table), and *pick place* (figure picks up a whisk and puts it down at a different location on the table). All action-related objects described above were placed on a table before and after the actions were performed. Actions also varied in their length (short or long). Animated stick figure videos were constructed based on these videos (for an example, see Figure 1). In total, 24 animated videos, differing in the type of action, perspective and length, served as stimuli in this experiment.



Figure 1. Exemplary depiction of the action *drink* in the *short* video condition, seen from third-(top) and first-person perspective (bottom). Stick figure videos were obtained from videos of an actress doing the everyday actions with real objects and wearing a motion capture suit.

1.3.3 Procedure

Participants were asked to reproduce the duration of an action by pressing down the spacebar. The start- and endpoints of a specific action had to be determined by the participants themselves, it was explicitly stated in the instructions that the start- and endpoint of the action would not necessarily coincide with the start and end of the video. Videos were presented in random order and each video was presented four times, resulting in a total of 96 trials. Each experimental trial started with an announcement which action would be presented. After 3 s one of the 24 videos was presented centrally with a resolution of 960x540 pixels. After the end of the video the screen first went blank for 1 s, followed by the presentation of a grey circle and instructions to reproduce the duration of the action. As a visual aid, the grey circled turned white while the spacebar was pressed down, i.e., during the interval reproduction. One additional trial at the beginning of the experiment served as a practice trial. The experiment was programmed in OpenSesame version 3.0.3 (Mathôt, Schreij & Theeuwes, 2012).

1.3.4 Data analysis

First, we tested the data for context effects. More specifically, we tested the effect of the previous (n-1, n-2,...) *subjective* trial (i.e., the previous production) and the previous *objective* trial (i.e., the objective duration of the action, as provided by the SEC algorithm described above, of the previous trial) on the current trial (i.e., the current production). For this analysis, we compared Linear Mixed Models (LMM) using the *lme4* package (version 1.1-10; Bates, Maechler & Bolker, 2012) in R version 3.2.2 (R Development Core Team, 2008). Reproduced action duration was entered as the dependent variable. Objective duration of the current trial, perspective and previous subjective or objective trial were entered as predictors, while participant and action were entered as random factor in each model. Following Taatgen & van Rijn (2011), we compared more complex models (i.e., models including n-1, n-2,...) with simpler models. The same model based approach was used to test for effects of perspective.

To test the data for the scalar property, the coefficient of determination (r^2) was determined by correlating the standard deviation of the reproduced action duration (*S*), averaged over all participants, with the mean reproduced duration (*M*) of each action in the long and short condition (i.e., for the 12 unique action-duration combinations, data from the different perspectives was pooled together). Additionally, the coefficient of variation ($CV = S \div M$) was calculated for each video and participant separately. An analysis of variance was carried out to test whether CVs differed across action durations.

1.4 Results

Figure 2 and Figure 3A depict the mean reproduced action durations for each action in the short and long version (i.e., for each objective duration). Visual inspection of the results suggests that shorter action durations were reproduced as lasting longer and, accordingly, longer action durations as being shorter. Consequently, reproduced action durations deviated systematically from the objective durations toward the mean duration of all intervals. Model comparisons showed that including subjective N-1 improved the model significantly ($\chi^2 = 63.80$, df = 1, p < .001). Thus, the subjective duration estimation in the previous trial influenced the duration estimation of the current trial ($\beta = 0.13$, p < .001). Adding N-2 to the model did not improve the goodness of fit ($\chi^2 = 2.09$, df = 1, p = .15). Following Taatgen and van Rijn (2011), we stopped including trials further back than N-2. Including additional components (N-3,...) did improve the fit of the model, but not the overall pattern of results.

Including perspective as a predictor of reproduced duration did not improve the predictiveness of the basic model ($\chi^2 = 1.49$, df = 1, p = .48), showing that manipulation of first- and third-person perspective did not alter duration reproductions (see also Figure 2). Consequently, data was pooled together for further analysis.

We also tested the effect of the *objective* N-1. In contrast to the subjective N-1, we found that adding the objective N-1 did not improve the model ($\chi^2 = 2.41$, df = 1, p = .12). Thus, there was a bias in the duration reproduction in the current trial toward the reproduction in the previous trial, but not toward the objective duration of the previous trial.



Figure 2. Mean reproduced action durations. Mean reproduced durations for each action (short and long version of an action are labeled with [s] and [l]), averaged over all participants. Violin plots illustrate the density distributions of participants' responses, i.e., reproduced action durations. Grey dots depict the objective duration as defined by the SEC algorithm. Generally, shorter durations were overestimated and longer durations underestimated, hinting at typical context effects.



Figure 3. Results depicting context effects (A) and the scalar property (B). (A) Mean reproduced durations (\pm *SD*, corrected for between-subject variability) for each action (short, long), averaged over all participants and first-/third-person perspective trials, plotted over the objective duration. Reproduced durations differ from the objective durations (diagonal dashed line): shorter durations were overestimated, whereas longer durations were underestimated. (B) Conforming the scalar property, regression of mean standard deviation (\pm *SD*, corrected for between-subject variability) against mean reproduced duration (circles) revealed a linear relationship (solid line) with $r^2 = .92$. Calculated coefficients of variation (triangles) did not differ significantly from each other.

The standard deviations *S* and mean reproduced durations *M* were highly correlated with $r^2 = .92$, p < .001 (Figure 3B). *CV* values of the different action durations did not differ significantly from each other, as revealed by a repeated-measures ANOVA performed on the *CV* values of all participants (*F*(11,242) = 1.04, p = .41).

1.5 Discussion

The present behavioral study investigated interval perception in real-world settings. Participants saw videos showing a stick-figure performing different everyday actions. Stick-figure movements were based on real human movements. We asked participants to reproduce the duration of the different actions performed by the stick-figure. Overall, our data shows features found in traditional laboratory studies, suggesting that those traditional findings can be generalized to our everyday world.

A consistent finding in studies on interval perception that use multiple, slightly different interval durations, are context effects. The duration of the previous trial (N-1 effects) and even the complete history of previously encountered interval durations within an experiment or experimental block (i.e., temporal context) effect the perception of the current interval (Acerbi, Wolpert & Vijayakumar, 2012; Bausenhart, Dyjas & Ulrich, 2014; Dyjas, Bausenhart & Ulrich, 2012; Gu & Meck, 2011; Jazaveri & Shadlen, 2010; Taatgen & van Rijn, 2011). Data of the current study exhibited a similar effect of temporal context. Interestingly, not the objective duration of the previously presented stimulus, but the subjective previous duration influences our current interval perception. Since the previous subjective duration was in fact the previous interval reproduction, it may be a better measure of how participants perceived and stored a given interval than the objectively measured duration of the previous interval. Furthermore, any given subjective N-1 trial comprises the subjective N-2 trial (as it is the N-1 of the N-1 trial), which itself comprises the subjective N-3 trial, and so on. Thus, subjective N-1 reflects the complete history of encountered intervals - the temporal context.

Additionally, data from the current study is in conformity with the scalar property of time perception. We found that variation in interval reproduction linearly increased with interval duration, and that the coefficient of variation did not differ across interval durations (see Figure 3). Thus, participants' timing sensitivity remained constant as the action durations varied from trial to trial. In principle, violations of or large variations in the coefficient of variance can hint at participants using counting strategies while performing interval perception tasks (Allman et al., 2014; Wearden & Lejeune, 2008). This was not the case in the current study.

Interestingly, we found no sign of an effect of first- versus third-person perspective. A possible explanation is that perceiving an action (or more general: a scene) from first-person perspective is not sufficient to induce a feeling of authorship (Ebert & Wegner, 2010) or embodiment. That is, in our experiment, participants only passively viewed the action being performed - they did not perform the action themselves.

The data gathered from the current study exhibited more variance than traditional time perception studies usually do. Typically, stimuli or to-be-timed events used in classic laboratory studies are simplified and have a clear and sharp on- and offset (e.g., an interval is marked by the appearance and disappearance of a circle on the screen). Here, on- and offsets of an action were not distinct events, but embedded in a series of movements (the stick-figure approached the table and reached for an object placed on the table before the tobe-timed action eventually started). Therefore, one possible explanation of the higher variance could be that participants encountered difficulties in determining or remembering the exact on- and offset of an action, because those time points were not clearly marked. However, in the additional experiment (see Supplemental Material) we found that participants in general have a very precise and consistent idea of when an actions started and ended, and how long it lasted. To shed more light on this matter, future research could test whether distinctiveness of on- and offsets has an effect on how well the interval marked by those events can be reproduced

Assuming that our perception and behavior is adapted and optimized to live in a highly complex environment, we can only fully understand perceptual and cognitive mechanisms when studying behavior in a highly complex environment. The current study shows that findings from artificial laboratory studies on interval perception can be generalized to more real-world like settings. Further, our findings highlight once again that any percept is influenced by and embedded in context.

1.6 Author Contributions

All authors contributed to the study design. Testing and data collection were performed by N. Schlichting and A. Damsma. N. Schlichting, A. Damsma and H. van Rijn performed the data analysis. N. Schlichting, A. Damsma and H. van Rijn drafted the manuscript, and E. E. Aksoy, M. Wächter, T. Asfour provided critical comments. All authors approved the final version of the manuscript for submission.

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1.10 Supplemental Material

In an additional experiment we aimed to validate the Semantic Event Chain (SEC) algorithm. The SEC algorithm outputs the start- and endpoint of an action

in a video, based on spatiotemporal hand-object relations. From this data the duration of an action can be calculate. In this additional experiment we asked participants to be *naive segmenters*, so they segmented the same stick-figure action videos that have been segmented by the SEC-algorithm, too. In this way, we were able to compare human data and the output of the SEC algorithm directly.

1.10.1 Materials

Participants. Twenty psychology students (mean age: 21.2 years, range: 17-28 years, 13 female) participated in the additional experiment and received partial course credit. All participants had normal or corrected-to-normal vision. Informed consent as approved by the Psychology Ethical Committee of the University of Groningen (15008-NE) was obtained before testing.

Stimuli. The exact same videos used in the main experiment were used in this additional experiment.

Procedure. Participants were asked to set the start- and endpoint of the action seen in the video so that only the action itself was captured in the new video. It was explicitly stated in the instructions that the start- and endpoint of the action would not necessarily coincide with the start and end of the video. Participants used a custom-made video-cutting application programmed in Matlab (version 8.05, The MathWork; see Figure S1 for an exemplary screenshot). Two slider buttons allowed participants to scroll through the video clip frame-by-frame to set the exact start- and endpoint of the action. Participants could take as much time as necessary on each trial. Also, they could replay the whole video and the selected segment as many times as they wanted. Each trial started with a presentation of an action video in the main video player. Only afterwards the slider, play and next buttons became activated for usage. Videos were presented in random order, and each video was presented one time only, resulting in a total trial number of 24. One additional trial at the beginning of the experiment served as a practice trial.

Data analysis. We performed linear regression of estimated durations with the durations defined by the SEC algorithm for each participant separately. Slopes close to a value of 1 indicate high similarity of the estimated to the SEC-defined durations. Thus, we performed a *t*-test comparing slope values against 1. The same analysis was performed for the data of the main experiment.

In addition, the same regression-analysis was performed on the action start- and endpoints data.

1.10.2 Results

Figure S2 summarizes the estimated durations of each action in the segmentation task. Because we did not find effects of perspective, we did not distinguish between first- and third-person view, but pooled the data together before performing the regression analysis. Mean slope of the regression analysis was 0.91 ± 0.16 (t(19) = 25.71, p < .001),



Figure S1. Exemplary screenshot of the video-cutting application. Videos or segments of the video were shown in the bigger, main window. The smaller windows to the left and right of the slider buttons displayed the video-frames of the start- (left) and endpoint (right) which participants set using the two slider buttons. Participants were allowed to watch the whole video or the selected segments as many times as they regarded as necessary (green buttons). By clicking the red next-button, the frame-number of the start- and endpoint was saved and a new video was loaded.

with $r^2 = .97 \pm .05$ (t(19) = 85.16, p < .001). Slope values were just significantly different from 1 (t(19) = -2.50, p = .022). The same analysis performed on the data from the main experiment resulted in a mean slope of 0.47 ± 0.18 (t(22) = 12.56, p < .001), with $r^2 = .86 \pm .14$ (t(22) = 29.95, p < .001). Slope values were significantly smaller than 1 (t(22) = -14.24, p < .001).

In Figure S3 the estimated start- and endpoints as well as the start- and endpoints as defined by the SEC algorithm are shown. The same regression analysis as for the produced durations was performed for estimated start- and endpoints separately. Linear regression of estimated start-points with objective start-points resulted in a mean slope of 0.95 ± 0.22 (t(19) = 19.13, p < .001), with $r^2 = .88 \pm .15$ (t(19) = 26.16, p < .001). Slope values were not significantly different from 1 (t(19) = -0.98, p = .34) For the endpoints we obtained a mean slope of 0.96 ± 0.08 (t(19) = 54.94, p < .001), with $r^2 = .99 \pm .01$ (t(19) = 804.50, p < .001). Endpoint slope values were just significantly different from 1 (t(19) = -2.47, p = .023).



Figure S2. Estimated action durations. Mean subjective (i.e., produced) durations (\pm *SD*, corrected for between-subject variability) as a function of objective action duration, averaged over first- and third-person perspective and all participants. Estimated durations differ only marginally from objective action durations (dashed line). Solid line depicts the regression line.



Figure S3. Estimated start- and endpoints of actions as a function of objective action start- and endpoints. Because the accurate productions of action durations could also result from shifted start- and end-points, we compared mean estimated start- (\pm *SD*, corrected for between-subject variability, A) and endpoints (\pm *SD*, corrected for between-subject variability, B) for each action, averaged over first- and third-person perspective and all participants. Estimated start- and endpoints differ only marginally from objective start- and endpoints (dashed line). Solid lines depicts the regression line.

1.10.3 Discussion

In this additional experiment we aimed to experimentally validate the SECalgorithm. Participants were asked to act as *naive segmenters* and mark the startand endpoint of a given action seen in a short video. The same videos that our participants had to segment were also segmented by the SEC-algorithm.

We found that experimental data was i) consistent with the algorithm and ii) internally consistent. This is the case for the duration and also the onset and

offset. Thus, the SEC algorithm segments actions in a way that human participants segment actions, too. Internal consistency means that the data exhibited only very little variation, in strong contrast to the main duration reproduction experiment.

Further, because people can estimate the onset and offset very well, we can conclude that the high variance and the bias toward the mean in the main experiment are not due to participants being unable to estimate where the actions starts and ends.



Integrated Intrinsic and Dedicated Representations of Time: A Computational Study Involving Robotic Agents

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Abstract

The computational modeling of cognitive processes provides a systematic means to study hidden and particularly complex aspects of brain functionality. Given our rather limited understanding of how the brain deals with the notion of time, the implementation of computational models addressing duration processing can be particularly informative for studying possible time representations in our brain. In the present work we adopt a connectionist modeling approach to study how time experiencing and time processing may be encoded in a simple neural network trained to accomplish time-based robotic tasks. A particularly interesting characteristic of the present study is the implementation of a single computational model to accomplish not only one but three different behavioral tasks that assume diverse manipulation of time intervals. This setup enables a multifaceted exploration of duration-processing mechanisms, revealing a rather plausible hypothesis of how our brain deals with time. The model is implemented through an evolutionary design procedure, making a very limited set of a priori assumptions regarding its internal structure and machinery. Artificial evolution facilitates the unconstrained self-organization of time representation and processing mechanisms in the brain of simulated robotic agents. Careful examination of the artificial brains has shown that the implemented mechanisms incorporate characteristics from both the 'intrinsic' time representation scheme and the 'dedicated' time representation scheme. Even though these two schemes are widely considered as contradictory, the present study shows that it is possible to effectively integrate them in the same cognitive system. This provides a new view on the possible representation of time in the brain, and paves the way for new and more comprehensive theories to address interval timing.

Keywords

Time representation, neural network model, artificial time perception, robotic sense of time, evolutionary self-organization, cognitive robotics

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1. Introduction

The perception and processing of duration play a key role in many of our daily activities from estimating the remaining time during exams and setting an appointment with friends, to enjoying music and dancing following the rhythm. Understanding how our brain perceives and reasons about time is a challenging issue that attracts rapidly increasing research interest in the neuroscience and cognitive science communities. Contemporary review papers and special journal issues have summarized and are testament to the new and burgeoning scientific findings in the field (Grondin, 2010; Ivry & Schlerf, 2008; Meck, 2005; Wittmann & van Wassenhove, 2009).

Despite the significant research interest that has been devoted to time, the neural underpinnings of the sense of time and the representation of duration in our brain remain rather poorly understood, with controversial theories attempting to explain experimental observations. Broadly speaking, there are two main approaches to describe how our brain represents time (Bueti, 2011; Ivry & Schlerf, 2008). 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 of 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 (Droit-Volet et al., 2007; Gibbon et al., 1984; Woodrow, 1930). This has inspired the subsequent pacemaker approach that uses oscillations to represent clock ticks (Large, 2008; Miall, 1989). Other dedicated models assume monotonically increasing or decreasing processes to encode elapsed time (Simen et al., 2011; Staddon & Higa, 1999). The second approach includes intrinsic explanations (also known as distributed) that describe time as a general and inherent property of neural dynamics (Dragoi et al., 2003; Karmarkar & Buonomano, 2007). According to this approach, time is intrinsically encoded in the activity of general-purpose networks of neurons. Thus, rather than using a time-dedicated neural circuit, time coexists with the representation and processing of other external stimuli. 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 (Matell & Meck, 2004; Meck et al., 2008). The SBF model assumes a dedicated timing mechanism in the basal ganglia that is based on monitoring distributed neural activity in the cortex.

The main limitation of the dedicated approach is its weakness in explaining modality-specific differences in time perception. On the other hand, intrinsic models are considered to have limited processing capacity, being inappropriate for exploring time 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.

Interestingly, the mechanisms assumed by the aforementioned models cannot universally process time both in the presence and the absence of continuous external input (e.g., on the basis of start–stop cues). Such a capacity, which is typical for biological cognitive systems, reveals an important lack of existing neurocomputational approaches. To address this issue, abstract clocklike mechanisms have been typically employed (Jazayeri & Shadlen, 2010; Taatgen et al., 2007). The present study aims to shed light on possible neurocomputational mechanisms that can effectively perceive time both in the presence and the absence of external stimuli.

Besides the human devised representations of time that have been discussed above, the time-processing mechanisms of our brain may exhibit different characteristics compared to the ones considered so far. Self-organized computational modeling can serve as a new tool that facilitates the exploration of alternative representations (Ruppin, 2002), and thus facilitates convergence in the time representation debate. This is the aim of the present study, which employs a simulated robotic setup to investigate possible neurocomputational representations of duration. The obtained results provide a fresh and unconventional view on the possible time-processing mechanisms of the brain, and may provide inspiration for future work in this field.

In contrast to the majority of existing time representation models, which start with a key assumption of following either the dedicated or the intrinsic approach and then hand code the details of the model, the present work does not make any a priori assumption but employs an automated design procedure to explore and propose efficient representations of time. To this end, the present study considers three different time-processing tasks, namely Duration Comparison, Duration Reproduction and Past Characterization that have to be accomplished by the very same robotic cognitive system. The 'behavioral' approach adopted in the current paper links with the Behavioral Theory of Timing (Killeen & Fetterman, 1988) and Learning to Time (Machado, 1997). These theories assume that the behavioral vocabulary of subjects supports duration perception, a view that has also been supported by recent experimental work (Gouvea et al., 2014).

We employ a Continuous Time Recurrent Neural Network (CTRNN) (Beer, 1995; Maniadakis et al., 2009a) to develop an 'artificial brain' for the robotic agent. An evolutionary design procedure based on Genetic Algorithms (Nolfi & Floreano, 2000) is used to search possible configurations of the artificial brain that can accomplish the three aforementioned tasks. This procedure promotes the unbiased self-organization of time representation in the cognitive system. The functional responsibilities endowed to the cognitive system as a

consequence of the robotic experimental setup, and the probabilistic optimization of CTRNN configurations as a result of the evolutionary exploration, do not only address what is possible in terms of time representation but, even more importantly, which are the more likely characteristics of such a representation.

Following a series of statistically independent experiments we obtain a set of artificial brains that fit the behavioral requirements of our study (i.e., accomplish the three duration-processing tasks). The automatically designed artificial brains are subsequently studied to reveal the characteristics of effective time perception mechanisms that may also be valid for interval processing in the brain. The obtained results show that a very effective modeling approach may result from combining the key characteristics of the dedicated and intrinsic time representations. In short, the neural circuits that support ordinary cognitive processing operate in an oscillatory mode that enables the encoding of elapsed time in the amplitude of the oscillation. This new representation facilitates the multimodal processing of time intervals as indicated by the accomplishment of the three different duration-processing tasks.

Interestingly, the perception and processing of time is particularly new in the field of robotic systems (Maniadakis & Trahanias, 2011). Work in the emerging research branch of robotic time perception is expected to significantly contribute to the seamless integration of artificial agents in human societies.

The remainder of the paper is structured as follows. The next section summarizes the experimental setup, describing (i) the simulated robot and the artificial brain used to endow it with cognitive and behavioral capacities, (ii) the behavioral tasks considered in the present work, and (iii) the evolutionary procedure employed to explore effective CTRNN configurations. In the following section we describe the obtained results, focusing on the internal mechanisms of the artificial brains. Then we discuss how our findings compare to the dedicated and intrinsic representations of time. In the last section we summarize the characteristics of the new time representation suggested by our experiments and we provide directions for future work.

2. Materials and Methods

The present work puts forward a new framework for the study of time perception that is based on robotic cognitive systems. The underlying computational approach exhibits unique characteristics in terms of exploring possible representations and mechanisms of interval timing, which account for:

- the placement of the robot in a specific environment where in addition to the processing of time it has to consider behavior planning and the interaction with objects;
- the uninterrupted sensory-motor flow and the continuous processing mode of the robotic cognitive system;
- the behavioral, as opposed to the symbolic expression of the robot's decision, in the form of a sequence of motor commands.

2.1. Experimental Setup

2.1.1. Simulation Environment

We have implemented a simulation of a two-wheeled mobile robot equipped with eight uniformly distributed distance, light and sound sensors. The distance sensor is mainly used during navigation to avoid the robot bumping into the walls. The light sensor is used to receive a task indicator informing the robot which one of the three tasks is to be considered at a given moment in the experiment. The sound sensor is used for the perception of temporal durations (i.e., the robot must perceive the temporal duration of emitted sounds).

The simulated robot operates in a rather simple environment with two walls located on its left and right side (Fig. 1). The robot has to perceive the duration of sound cues and drive without bumps along the corridor that is formed by the two walls, behaving as requested by the scenario of the particular task. Given that the experiments considered in the present study do not require complex manipulations of moving objects, we set one simulation step of the environment to correspond to 100 ms. Therefore, a real-world behavior expressed for 10 s corresponds to 100 simulation steps in the virtual environment considered in the present study.

The selected time step is sufficiently small to support the interaction of the robot with the environment and additionally it is sufficiently large to reduce the computational resources required to design an artificial brain to the order of approximately one day (when running on a single computer). Similar time steps are typical for robotic simulation experiments, and have been used extensively in our previous studies on time perception (Maniadakis & Trahanias, 2012; Maniadakis et al., 2009a, 2009b, 2011). Interestingly, the duration of 100 ms is frequently assumed to correspond to the resolution of cognitive steps in our brain (Dehaene & Naccache, 2001; van de Par & Kohlrausch, 2000).

2.1.2. The Brain of the Robot

A three-level Continuous Time Recurrent Neural Network (CTRNN) (Beer, 1995; Maniadakis & Tani, 2008) is used to provide the artificial agent with behavioral and cognitive capacities. This type of network represents knowledge in terms of internal neurodynamic attractors and it is therefore particularly appropriate for implementing cognitive capacity that is inherently continuous, similar to our mind.



Figure 1. A graphical representation of the experimental setup. The robot is depicted as a small circle at the beginning of the corridor. Depending on the task, the robot is asked to either reach one of the two goal positions as shown in part (a), or make a sudden 180° turn as shown in part (b).

The network consists of four neurons in the upper level, six neurons in the middle level and four neurons in the lower level. Full intra- and interlevel connectivity is assumed in the model. Synaptic weights are determined by an evolutionary procedure (described below) and they remain constant during task testing. Similar to previous studies (Paine & Tani, 2005; Yamauchi & Beer, 1996) CTRNN neurons are governed by the standard leaky integrator equation:

$$\frac{\mathrm{d}\gamma_i}{\mathrm{d}t} = \frac{1}{\tau} \left(-\gamma_i + \sum_{k=1}^R w_{ik}^s I_k + \sum_{m=1}^N w_{im}^p A_m \right) \tag{1}$$

where γ_i is the state (cell potential) of the *i* – th neuron. All neurons in a network share the same time constant $\tau = 0.25$ in order to avoid explicit differentiation in the functionality of CTRNN parts. This time constant is a key parameter for the functionality of the model, because it synchronizes the processing mechanisms of the network with the rate of sensory-motor information flow.

The state of each neuron is updated according to external sensory input *I* weighted by w^s , and the activity of presynaptic neurons *A* weighted by w^p . After estimating the neural state by eqn. (1), the activation of the *i* – th neuron is calculated by the non-linear sigmoid function according to:

$$A_i = \frac{1}{1 + e^{-(\gamma_i - \theta_i)}} \tag{2}$$

where θ_i is the activation bias applied on the *i* – th neuron.

All sensory information is projected only in the middle level of the CTRNN. This allows different functional roles to be developed in each layer of the network. The four neurons at the lower level of the CTRNN are connected to a motor neuron that controls the wheels of the robot. The speed for each of the two wheels is determined by a pair of neurons operating according to the flexor/extensor principle (i.e., one increases and the other decreases the speed of the wheel). Let us assume that at a given time step, the activation of the motor neuron is A_m . Then, the left and right wheel speed of the simulated robot is given by:

$$speed_{l} = 0.4 + 0.6A_{m}$$
 $speed_{r} = 0.4 + 0.6(1 - A_{m})$ (3)

Following this approach the agent moves with a constant total speed, while the activation A_m controls the direction of movement.

2.2. Behavioral Tasks

To explore time representations through artificial neural network self-organization, the present study considers simple maze tasks that have to be achieved by a simulated robotic agent, similar to Blynel and Floreano (2003), Maniadakis and Trahanias (2006), and Ziemke and Thieme (2002). Each one of the three tasks addresses a different aspect of duration processing. More specifically, there are two main types of experiments in the field of interval timing memorization, one focusing on duration comparison and the other on the reproduction of an earlier presented duration (Taatgen & van Rijn, 2011). In the present study we explore both of these types, considering additionally a simplified example of past time stamping. The three tasks explored in the present work are described in detail below.

2.2.1. Duration Comparison

The experiment assumes that the robot perceives two time intervals A and B, compares them and drives to the end of the corridor turning either to the left side in the case that A was shorter than B, or to the right side in the case that A was longer than B (see Fig. 1a).

The experiment starts with the simulated mobile robot located at the beginning of the corridor environment. The artificial agent remains at the initial position for a short initialization phase of 10 simulation steps, where it experiences a light cue indicating that the experimental procedure for the Duration Comparison task will follow (see Fig. 2a). Subsequently, after a short preparation phase, the agent experiences two sounds having temporal durations A and B, both of them randomly specified in the range [10, 100]. The two sounds are separated by a predefined rest period of ten simulation steps. Just after sound B, the agent is provided 20 simulation steps to compare A and B, decide which one was longer and prepare its motion strategy. At the end of this period the robot is provided a 'go' signal and it starts navigating across the corridor. In order to successfully complete the task, the agent has to navigate to the end of the corridor and turn right in the case that the A interval was longer, or, turn left in the case that the A interval was shorter (than B).

To evaluate the response of the artificial agent we mark two different positions in the environment that are used as goal positions for the robot, as shown in Fig. 1a. Depending on whether *A* was actually longer than *B* or not, we select the correct goal position and we measure the minimum distance *D* between the agent's path and that goal position (i.e., when A < B the agent should approximately reach Goal1, but when A > B the agent should approximately reach Goal2). Additionally, during navigation, we consider the number *Bumps* of robot bumps into the walls. Overall, the success of the agent to a given duration comparison $i \in \{A > B, A < B\}$ is estimated as:



$$S_i = \frac{100}{D(Bumps+1)} \tag{4}$$

Figure 2. The structure of (a) the Duration Comparison, (b) the Duration Reproduction, and (c) the Past Characterization experiments.

By maximizing $S_{A>B}$ and $S_{A<B}$, we aim at minimizing the distance from the goals, therefore producing responses at the correct side of the corridor as well as avoiding bumping into the walls. The total capacity of the robot to accomplish the Duration Comparison task considering both possible relations between *A* and *B* intervals, is estimated as:

$$FIT_{\rm DC} = S_{A>B} \cdot S_{A$$

2.3. Duration Reproduction

The experiment assumes that the robot perceives a time interval A and reproduces its duration by moving forward for the same amount of time. To demonstrate the end of the reproduction period, the robot makes a quick 180° turn as shown in Fig. 1b.

The experiment starts with the robot located at the beginning of the corridor. After a short initialization period, the agent experiences a light cue indicating that the experimental procedure that will follow concerns the Duration Reproduction task (see Fig. 2b). Subsequently, the agent experiences a sound with temporal duration A, which is randomly specified in the range [10, 100]. Just after this sound, the agent is provided 20 simulation steps to prepare its behavioral response. Then, the agent is provided a 'go' signal and it starts navigating towards the end of the corridor. In order to successfully complete the task, the agent has to move forward navigating freely inside the corridor, for a time interval that equals A. As soon as the robot believes that the A interval has been completed, it immediately has to make a 180° turn, and continue navigation facing the beginning of the corridor.

To evaluate the response of the artificial agent we consider its direction of motion in the whole period of duration reproduction. To enable the robot to express the 180° turn in a sequence of actions, we examine the robot's behavior for A + 30 simulation steps (i.e., a period slightly longer than A).

During the reproduction of the *A* interval, the robot must move mostly forward, which means its direction *Dir* should be approximately 0° . Just after the completion of *A* and for the next 30 steps, the robot must turn in the opposite direction, steering at 180°. The success of the agent in the duration reproduction task is numerically evaluated by:

$$FIT_{\rm DR} = \frac{1}{\sum_{1}^{length(A)} Dir^2 + \sum_{length(A)+1}^{length(A)+30} (180 - Dir)^2}$$
(6)

By maximizing FIT_{DR} , we aim at minimizing the difference between the direction in which the robot moves and the optimal moving direction as explained above.

2.4. Past Characterization

The procedure assumes that the robot experiences a sound and after some time it is asked to judge whether this particular experience was a short or a long time ago. The robot responds by navigating along the corridor and turning either to the left side in the case that the sound event happened in the distant past, or to the right side in the case that the sound appeared in the recent past (see Fig. 1a).

The experiment starts with the simulated mobile robot located at the beginning of the corridor. After a short initialization period, the agent experiences a light cue indicating that the experimental procedure that will follow concerns the Past Characterization task (see Fig. 2c). Subsequently, a preparation interval follows with duration *TD* randomly specified either in the range $TD \in [15, 25]$ (for the case of distant past), or $TD \in [65, 75]$ (for the case of recent past). After a sound is

emitted, a waiting period follows that is dynamically specified as W = 100 - TD. As a result, the pair of durations *TD* and *W* determines whether the sound experience of the agent was a long or a short time ago.

At the end of the waiting period the agent is provided a 'go' signal and it starts navigating towards the end of the corridor. To evaluate the response of the robot we use the two goal positions that were also employed in the Duration Comparison experiment (see Fig. 1a). Depending on whether the sound was actually experienced by the agent in the distant or the recent past, we select the appropriate goal position and we measure the minimum distance *D* of the agent's path from that goal (i.e., in the case of distant past the agent should steer towards Goal1, while in the case of recent past the agent should steer towards Goal2). To evaluate the robot's response we use two success measures S_{distant} and S_{recent} defined according to eqn. (4). Overall, the capacity of the robot to accomplish the Past Characterization task is estimated as:

$$FIT_{PC} = S_{distant} \cdot S_{recent} \tag{7}$$

2.5. Evolutionary Design

We employ a Genetic Algorithm (GA) to explore possible cognitive mechanisms that enable the artificial agent to perceive and process time in accomplishing the three behavioral tasks described above (Nolfi & Floreano, 2000). This approach is based on using optimization procedures to train agents in accomplishing tasks. Readers not familiar with evolutionary optimization may simply omit the rest of this section, considering this part of the work as a black box procedure that accomplishes parametrical tuning of the CTRNN.

GAs accomplish an abstracted simulation of biological evolution by producing a sequence of robot generations that are gradually fitted to the design criteria specified. In the current work, these criteria consist in the successful accomplishment of the three duration-processing tasks. We use a population of 1000 artificial chromosomes, each one encoding a different CTRNN configuration, or a different robot brain. Each candidate CTRNN solution is tested on a randomly initialized version of the three tasks. To get an estimate of the CTRNN's time-processing capacity, we combine in a multiplicative manner the performance metrics associated with each one of the three tasks. Therefore, the global fitness of a chromosome is defined as follows:

$$F = FIT_{\rm DC} \cdot FIT_{\rm DR} \cdot FIT_{\rm PC} \tag{8}$$

This is the fitness function that drives the exploration of CTRNN configurations. By maximizing F, we get robot brains that can satisfactorily accomplish the three duration-processing tasks considered in the present study.

We have used a standard GA process with survival of the fittest individuals along consecutive generations (Nolfi & Floreano, 2000). Real-value encoding is used to map synaptic weights and neural biases of the CTRNN into chromosomes. During reproduction, the best 30 individuals of a given generation mate with randomly selected individuals using single-point crossover, to produce the next generation of CTRNNs. Crossover facilitates transferring knowledge from one generation to the next. Mutation corresponds to the addition of up to 25% noise in the parameters encoded in the chromosome, with each CTRNN parameter having a probability of 4% to be mutated. Mutation facilitates the exploration of new, gradually more effective solutions that will be transferred to the next generation (through crossover).

In all evolutionary runs the randomly initialized population is evolved for a predefined number of 500 generations. The present work focuses on temporal cognition mechanisms, rather than the robotic behaviors, which means that robot responses should be mainly considered as proofs of the time-processing capacity of the cognitive system. In some of the obtained results the details of the robotic behaviors could improve further by using a very long evolutionary procedure. However, optimal robotic behaviors would probably be a result of overfitting. This is rather inappropriate for the present study that wants to explore the qualitative characteristics of time-processing capacities in artificial cognitive systems. The evolutionary procedure was therefore interrupted after the predefined number of 500 generations, which proved adequate for the successful evolution of time-processing skills.

3. Results

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We have conducted ten statistically independent evolutionary runs to explore possible neural mechanisms that are capable of accomplishing the three duration-processing tasks described above. The evolutionary procedures converged successfully in six of the runs, producing artificial brains that are able to perceive and process time. The remaining four ineffective artificial brains were excluded from our study. Theoretically speaking, it is possible to increase the success rate of the evolutionary procedure by adjusting mutation and crossover operators. However, our focus is on time-processing mechanisms and since the details of artificial evolution do not affect the machinery of CTRNN solutions, it is outside the scope of the present study to identify the mutation and crossover rates that result in the most effective evolutionary scheme.

In order to obtain insight into the mechanisms self-organized in the robot brains, we have investigated neural activity in the successfully evolved CTRNN configurations. Interestingly, even if the evolutionary procedures were statistically independent, all obtained results show (qualitatively) similar internal mechanisms. Below we discuss the characteristics that are common between successful artificial brains, using as a working example one representative of the CTRNN configurations.

It is necessary to note here that the evolutionary procedure is searching for CTRNN mechanisms capable to successfully accomplish the three durationprocessing tasks discussed above, but there is no explicit request for implementing duration-processing mechanisms. However, as is discussed below, the functionality of the CTRNN relies on a fully emergent mechanism that resembles duration counting.

3.1. Duration Comparison

To assess the duration comparison capacity of the model, we have tested multiple pairs of random durations. In all cases the robot could robustly perceive the duration of intervals, compare their lengths, and finally respond successfully by driving to the end of the corridor and turn towards the side that corresponds to the longest interval. The behavior of the robotic agent when comparing two time intervals with durations of 45 and 60 simulation steps is shown in Fig. 3a. The robot, rather than navigating in the middle of the free corridor space and then



Figure 3. The behavioral responses of the robot in the three tasks considered in the present study. (a) Duration Comparison. In the first case the robot compares intervals A and B with durations of 45 and 60 simulation steps respectively. In the second case the robot compares intervals A and B with durations of 45 and 60 simulation steps. (b) Duration Reproduction. The first plot shows the behavior of the agent during the reproduction of a time interval with length 71. The robot moves forward, making a sudden turn backwards when it believes that the reproduced period is completed. The second plot shows the sinusoidal of the robot's moving direction (*y*-axis), during the duration reproduction task. Initially the robot moves at approximately zero degrees ($\sin[0] = 0$), and as soon as the reproduction time approaches the end it turns to 90° (i.e., $\sin[180] = 0$) to face the beginning of the corridor. The bell curve is centered at 74 simulation steps, which indicates that the robot reproduces the memorized duration with sufficient accuracy. (c) Past Characterization task. The two plots show that the robot responds correctly to the experience of sound either in the distant or recent past.

turning either left or right, adopts a motion strategy that distinguishes between the two options very early. This is because our model does not assume an explicit working memory module that temporally stores comparison results to be used when the robot approaches the end of the corridor. Alternatively, in our model, the dynamics of neural activity encode the result of the comparison, which slightly but constantly affects the motion plan, gradually moving the robot to the chosen side.

The neural activities in the three layers of the CTRNN when the robot compares two time intervals with lengths A = 45 and B = 60, are shown in Fig. 4. Each subplot corresponds to a different layer of the CTRNN. In all plots the first two black vertical solid lines indicate the *A* period, and the next pair of black vertical dotted lines indicate the *B* period. The fifth vertical line corresponds to the time that the 'go' signal is given to the robot.

In all layers of the CTRNN the activity of neurons is mainly governed by oscillatory dynamics. The phase of the oscillation is largely determined by the time constant τ used in the equation of the leaky integrator neuron model and the simulation step used in our experiments. The synchronization of this particular triplet (phase, time constant, simulation step) is critical for the functionality of the model. Changes in any of these three parameters may destroy the functionality of the cognitive system in the given experimental setup.



Figure 4. The neural activity in the three layers of the CTRNN during a Duration Comparison task with A = 45 and B = 60. Each plot corresponds to a different layer of the CTRNN.

Oscillations are particularly useful from a time representation perspective, because they provide a means for measuring time intervals (i.e., by counting the number of oscillations) as is suggested by dedicated timing representations (Gibbon et al., 1984; Large, 2008). At the same time, from a robot control perspective, oscillatory dynamics enable steering the robot in the desired direction. Therefore, oscillating mechanisms seem particularly appropriate to support both the cognitive and the behavioral requirements of the time-processing tasks. This is in support of the theories promoting a strong correlation between embodiment and time perception (Craig, 2009; Gouvea et al., 2014; Wittmann, 2009).

Besides the fact that the task is clearly separated into two distinct phases of (i) perception and (ii) action, in Fig. 4 we see that the same neurons are activated for the whole duration of the task. In other words, there are no neurons devoted only to time perception. The neurons supporting ordinary cognitive tasks undertake additionally the responsibility of encoding the flow of time as is suggested by intrinsic time representations. Moreover, given that 100 simulations steps in our study correspond to 10 s in the real world, the present results postulate that intrinsic time representations can be functional not only for very short but additionally for sufficiently long time intervals (Maniadakis et al., 2014).

The examination of neural activity in the three network layers shows that there is a slight differentiation of the upper part with respect to time perception. In particular, in some of the upper-level neurons, the amplitude of the oscillation increases as long as the agent experiences sound (see for example the activity of the upper-level neuron depicted with a thick line, when the agent experiences either interval A or B, in Fig. 4). This suggests that duration may be encoded in the amplitude of the oscillatory activity. The latter observation complements pacemaker–accumulator models that assume each oscillation to correspond to one temporal unit, or one clock tick (Gibbon et al., 1984). According to our results the parameters of the oscillation (in our case, the amplitude) can be actively used for counting and encoding the elapsed time. In other words, oscillations may not only operate as passive ticks, but they might be actively involved in the processing of time.

However, apart from interval timing, the increasing amplitude may also encode the probability for a left- or right-directed robot response. Unfortunately, there is no easy way to distinguish whether the increasing amplitude corresponds to either duration perception, or decision making, or both, similar to the problem of explaining the ramplike activity that has been observed in several brain areas (Matell & Meck, 2004). Our intuition from experimenting with the model is that the higher-level activity measures time, in support of the decisionmaking procedure similar to results by van Rijn et al. (2011), and thus duration perception and decision making coexist in the model.

3.2. Duration Reproduction

In this task, the robot has to memorize and reproduce the length of an experienced duration. The trace of the robot when reproducing a temporal interval of 71 simulation steps is depicted in the first plot of Fig. 3b. To assess the accuracy of duration reproduction we examine how the direction of robot's motion evolves over time. The second plot of Fig. 3b shows the sinusoidal of the direction of the robot during task execution. The sinusoidal of the direction is close to zero during the first 60 steps of the robot's motion, indicating that the robot moves approximately at 0° (i.e., $\sin[0] = 0$). When 60 steps have passed, the robot registers that the reproduction period is about to finish and it starts turning. This is indicated by the gradual increase of the sinusoidal of the robot's direction (i.e., $\sin[90] = 1$), which soon after that drops again to approximately zero (i.e., $\sin[180] = 0$). According to the second plot of Fig. 3b, the robot's turn is centered on 74, indicating that the robot has approximately memorized and reproduced the original time interval of length 71.

We now turn to the internal dynamics in the upper layer of the CTRNN (neural activity in the middle and lower layer also follow oscillatory patterns, but in the discussion we concentrate on the upper layer of the network, which exhibits more time-relevant activity). The two black vertical lines shown in Fig. 5a delineate the period of time experiencing, while the third vertical line corresponds to the time that the 'go' signal is given. During sound perception the upper part of the CTRNN exhibits a counting-like functionality with the amplitude of the oscillation increasing gradually as time goes by (see neural activity depicted with thick lines). Interestingly, in the subsequent duration reproduction

phase, one of the thick-drawn neurons shows an inverse pattern of neural activity with the amplitude of the sinusoidal gradually decreasing, similar to a reverse counting procedure.

Based on these observations, it seems that the artificial agent develops a count-up mechanism that is used for duration observation and a count-down mechanism that is used for duration reproduction. Actually, this constitutes a novel explanation that is rarely considered in the literature. Note that a full reset of interval counting at the end of the sound-experiencing phase (Spencer et al., 2009), would render the count-down mechanism inappropriate for the given task. In such a case, more resources might be required by the cognitive system in order to explicitly memorize the experienced duration and repetitively compare the memorized duration with the currently reproduced duration.

The Duration Reproduction task provides the means to explore whether the observed mechanisms exhibit the scalar characteristics that are typical observed in biological timing mechanisms (Lejeune & Wearden, 2006). Scalar timing implies that (i) measurements should vary linearly and near-accurately as time increases and (ii) the variance of the perceptual mechanism increases as the duration of time also increases. We test the performance of the CTRNN in three sets of ten randomly initialized Duration Reproduction trials (i.e., each trial is performed with different additive noise on the sensors supporting robotenvironment interaction). The first set concerns intervals of 37 simulation steps, the second concerns intervals of 50 simulation steps and the last, intervals of 85 simulation steps. Since the robot does not provide an instant response but specifies the end of the reproduction interval with a sequence of actions resulting in a turn of 180°, we have used the simulation step with a maximal change in the robot's direction as the indicator of the end of reproduction. Table 1 summarizes the success rate of the robot in reproducing the aforementioned intervals. The mean and the variance of the robot's estimates of the observed intervals are shown in the last two columns of the table. The average of the estimated intervals remains close to the true time in all three cases, satisfying mean accuracy, and the variance increases as the robot experiences longer intervals. These observations indicate that CTRNN timing largely complies with the scalar property.

However, the self-organized mechanisms also exhibit some limitations. More specifically, the average time estimates shown in Table 1 are constantly shifted to the right compared to the true time value. This might be due to the simplified approach we have used to select the point indicating the end of reproduction. Additionally, the scalar property assumes a constant *coefficient of variation*. However, this is not true for our model, indicating a direction for future advancements. Nevertheless, it is worth emphasizing that the two main characteristics of the scalar property (i.e., mean accuracy and scalar variance) have been self-organized without any explicit instructions by the modeler. We

Table 1.

The performance of the simulated robot in the three sets of randomly initialized Duration Reproduction trials

True time		Reproduced time in 10 random trials								Mean	Variance	
	1	2	3	4	5	6	7	8	9	10		
37	41	42	44	45	44	44	42	44	42	43	43.1	1.49
50	51	55	55	55	55	52	51	52	56	52	53.4	3.44
85	88	88	93	90	87	88	87	87	92	91	89.1	4.4

assume that a constant coefficient of variation may easily emerge when constraints relevant to the scalar property are introduced in the evolutionary design procedure.

3.3. Past Characterization

In this task, the robot has to characterize the temporal distance of a given sound cue, choosing whether the sensory experience was a long or a short time ago. The robot expresses its belief by navigating to the end of the corridor and then turning either to the left or the right side (left corresponds to distant past, while right corresponds to recent past). The behavior of the robot for each of the two cases is shown in Fig. 3c. In the first case, the robot experiences a sound 70 steps prior to the go signal, while in the second case the robot experiences a sound 27 steps prior to the go signal.

The activity in the upper level of CTRNN neurons for each of the two cases is shown in the two plots of Figs 5b and c. The onset of sound is indicated by the first vertical line. The second vertical line shows the time that the 'go' signal is given. Examining the internal activities of the CTRNN, we observe that the sound triggers a mechanism that resembles countdown as observed in the Duration Reproduction task. More specifically, in the distant past condition the amplitude of the sinusoidal increases with the emission of sound (see thick lines in the first plot of Fig. 5b). This increase is followed by reverse counting that continues until the amplitude has a sufficiently low value, indicating that it was a long time ago since a sound was experienced. In the recent past condition (see the plot of Fig. 5c) the amplitude of the sinusoidal increases again with the emission of sound, but now there is not enough time for the amplitude to decrease and thus the robot can easily understand that it has been a rather short time since the last presence of the sound.

Overall, by considering the level of decrease in the amplitude of the oscillation, the robot distinguishes between sound observation in the distant or recent past, and implements diverse behavioral responses for the two cases of past characterization (see Fig. 3c). In other words, the amplitude of the oscillatory neural activity can not only operate as a possible accumulator, but may also



Figure 5. The activity in the upper layer of the CTRNN in (a) the Duration Reproduction task where the length of the perceived and reproduced interval is depicted with a gray box, (b) the Past Characterization task for the case of time experiencing in the distant past, and (c) the Past Characterization task for the case of time experiencing in the recent past.

integrate an inverse counting capacity, therefore being actively engaged in decision making.

3.4. Summary

To develop a global view of the functionality of the model, we outline the mechanisms enabling the processing of time. First, it is necessary to note that cognitive activity in the CTRNN is guided by properly shaped neurodynamic attractors encoding the current state of the network (Beer, 1995). A neurodynamic mechanism related to the quantitative properties of time is likely to exist in the upper level of the network where cognitive dynamics follow an attractor of increasing size that is correlated with the duration of the time elapsed. The increasing size of the attractor during time perception is the dynamic analogy of a discrete accumulator that counts clocklike tics. In the Duration Comparison task, depending on the relative size of the attractors during the perception of *A* and *B* intervals, the cognitive system decides to follow either the left-directed motion path, or the right-directed motion path, implemented by separate behavioral attractors. In the case of the Duration Reproduction task, the increasing perceptual attractor in the upper level of the CTRNN encodes the duration of the presented interval, which is then used as a starting point of the counting-down procedure that enables accurate reproduction. When the amplitude of the oscillation is close to zero, the agent makes a fast turn towards the beginning of the corridor to indicate the end of the interval. Finally, in the Past Characterization task, the counting-down procedure implemented as a gradually decreasing oscillation amplitude is employed to measure the distance to the past. In the case that the event has occurred in the distant past, the amplitude decreases to approximately zero and the robot initiates the left-directed path. When the perceived event occurred in the recent past, there is not enough time for the amplitude to decrease and the robot follows the right-directed motion path.

Oscillations guide neural activity in all three layers of the CTRNN facilitating the integration of top-down and bottom-up effects on robot cognition. The topdown effect regards the processing of time and the transformation of time judgments to motion commands. The bottom-up effect regards the abstraction of a numerical notion of time out of the lower-level oscillations as well as the modulation of motion planning by interaction with the environment. Even if different roles are assumed for the three layers of the CTRNN, their performance is not isolated and they remain strongly and bidirectionally linked on the basis of oscillatory activity. In other words, what is functional is the composite CTRNN model rather than the isolated layers of neurons. Capitalizing on the sense of the flow of time provided by these oscillations, the robot implements a counting-like mechanism that facilitates the accomplishment of the given duration-processing tasks. Moreover, in contrast to the behavioral approaches such as the Behavioral Theory of Timing (Killeen & Fetterman, 1988) and the Learning to Time (Machado, 1997), we have not observed the formulation of any type of adjunctive or sub-behaviors that facilitate interval timing.

To explore the generalization of the CTRNN mechanisms and their applicability in processing intervals in the order of a few tenths of seconds, we have run supplementary simulation experiments with the robot considering durations of up to 200 simulation steps (these correspond to 20 s in the real world, as indicated by the simulation step of 100 ms used in our study). The new group of experiments showed that by using the CTRNN mechanisms described above, the robot can successfully accomplish the three tasks, effectively processing the extended durations.

Focusing on duration processing and according to the observed neurodynamics, the passage of time is intrinsically encoded in the ordinary activity of neurons that takes care of the behavioral accomplishment of tasks. However, pure oscillatory activity is not enough for the composite system to be aware of interval duration. A higher-level process is necessary to monitor lower-level activity and extract quantitative measurements encoded in the amplitude of the oscillation. Interestingly, the implemented counting-up and counting-down mechanism is appropriate to process time both in the presence and the absence of external sensory input. The latter constitutes a unique feature of our work, which differentiates the present CTRNN model from previous neurocomputational models. The interval timing mechanism that emerges from our model is in agreement with the proposal for a higher evel representation of duration (van Wassenhove, 2009).

4. Discussion and Conclusions

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The present work adopts a computational modeling approach to investigate time representation in cognitive systems. Undoubtedly, the complexity of the CTRNN model used in our study can hardly compare to the complexity of the brain and we therefore do not argue to have uncovered all details of time processing in the brain. In contrast, the aim of the present work has been to explore possible representations of time, focusing on the qualitative characteristics of emergent (rather than preconstrained) representations in computational cognitive systems. Such an approach is particularly useful to propose alternative but feasible and biologically plausible explanations on interval timing, whose validity remains to be experimentally studied in the brain. In other words, even if the present study does not aim to introduce 'The Model' of interval timing, many characteristics of the observed timing mechanisms may be established as valid brain features. These may regard the perception of duration by the higher levels of the cognitive system, the combination of the oscillatory activity with amplitude adaptations, the probabilistic information that may be encoded in the amplitude, and the role of counting and inverse counting mechanisms when dealing with duration-processing tasks. The present computational study may be a significant source of inspiration for enriching existing theories on the functionality of the brain and thus enable neuroscientists to come up with new and more powerful explanations.

The experimental approach followed in the present study accomplishes an unbiased exploration of possible time representations by considering (i) the functional integration of time processing with other skills, in the framework of time-dependent robotic behavioral tasks, (ii) the embodied exploration of duration-processing capacity in dynamic and noisy experimental setups that improve the generalization of the computational model, and (iii) the ability of the 'very same model' to address not only one, but three different duration-processing tasks.

Interestingly, the results obtained in the present study demonstrate that it is possible to integrate the dedicated and intrinsic models of time into a new enhanced modeling approach with more explanatory power. More specifically, our robotic experiments suggest that:

• Interval timing can be encoded in the activity of neurons supporting ordinary cognitive tasks. This is the main idea behind intrinsic time representation. So far, the main argumentation against intrinsic approaches (Karmarkar & Buonomano, 2007) has been that they can only be useful for the processing

of short duration intervals and thus they have rather little to offer in the processing of longer durations which are typically considered in human daily activities (even if the processing of long durations should not necessarily assume oscillatory activity — e.g., Staddon & Higa, 1999). Our study has clearly shown that, by exploiting oscillatory dynamics, it is possible to encode time in the activity of neurons that support other cognitive capacities and this approach can effectively be used for the processing of relatively long temporal durations, facilitating the accomplishment of complex behavioral tasks.

• Counting oscillations can effectively facilitate the estimation of the elapsed time as suggested by dedicated representation models (Gibbon et al., 1984; Large, 2008). However, our model shows that duration can be encoded in the parameters of the oscillatory activity (in the amplitude of the oscillation in the case of our study). In other words, oscillations can not only implement 'ticks' but also additionally provide the space for storing the estimated duration. According to our results, oscillations may not necessarily serve as passive pace-keepers, but they can be actively involved in the processing of time.

Moreover, our study suggests that time perception can be considered as a higherlevel capacity that emerges from monitoring the activities and interactions of other neurons. This is in agreement with the second-order abstracted representation of time proposed by van Wassenhove (2009). In our model a counting-like mechanism is self-organized in the upper part of the CTRNN, which in fact receives no direct sensory input, but accomplishes encoding the elapsed time in the amplitude of the oscillatory neural activity. However, key aspects of time perception remain strongly linked with embodiment issues and the control scheme used to direct the motion of the agent, as suggested by Craig (2009) and Wittmann (2009).

4.1. Possible Computational Biases in the Timing Mechanisms

A major goal of the current work was the study of interval timing, starting from a minimal set of modeler-imposed assumptions regarding the functionality of internal mechanisms. Nonetheless, there is a chance that the unavoidable decisions we have taken with respect to the implementation of our experiments may have introduced bias in the final result. In particular, certain implementation issues are known to affect how the observed mechanisms are shaped. These account for:

- the hierarchical structure of the CTRNN that promotes the modular functionality of the implemented system (Maniadakis & Tani, 2008);
- the time constant used in the implementation of CTRNN neurons and the 100 ms simulation step used in our experiments, which together have set the phase of oscillations and have reduced the applicability of the current model when different simulation steps are considered;

- the leaky integrator neuron model and the continuous processing of the CTRNN that enforces the encoding of behaviors and mental states as attractors in the internal dynamics of the CTRNN;
- the robotic embodiments that assume the integration of time-processing capacity with behavioral skills and sensory-motor processing.

Note, however, that nearly the same experimental setup has been used in our early work (Maniadakis & Trahanias, 2012) focusing on Duration Comparison, where the CTRNN did not give rise to self-organized oscillatory dynamics but a ramp-like neural activity. Consequently, there seems to be adequate evidence that the technicalities of our implementation do not impose hard constraints that strongly bias the emergent time-processing mechanisms. This is due to the fact that the main difference between the previous work and the current study regards the number of tasks considered. While the first exploresd only one task (aspect) of interval timing, the current study explores three different tasks (aspects), therefore accomplishing a multifaceted exploration of interval timing.

Intuitively, the inclusion of a limited number of tasks may be considered as the main external bias on the obtained results. The exploration of three timing tasks, when one can easily think of many other tasks to address a much broader set of duration-processing aspects, is likely to have affected the development of CTRNN neurodynamics. Even though we are not aware of other neurocomputational models that can simultaneously accomplish multiple tasks, we strongly believe that in order to obtain insight into interval timing mechanisms our models should address the broader possible set of timing capacities. This will improve the generalization of the timing mechanisms and will strengthen the biological plausibility of our assumptions.

In conclusion, the present computational study shows that the two main approaches for the representation of time existing today, namely the dedicated and intrinsic representations, can be effectively combined into a new comprehensive theory that integrates their key characteristics. Following our results, the two approaches should no longer be regarded as opponents, but rather as key ingredients of a more flexible representational scheme with enhanced explanatory power for real brain observations. Our future work will mainly involve experiments that will consider simultaneously a larger number of interval timing tasks in artificial systems.

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