Synchronisation effects on the behavioural performance and information dynamics of a simulated minimally cognitive robotic agent

Renan C. Moioli · Patricia A. Vargas · Phil Husbands

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Abstract Oscillatory activity is ubiquitous in nervous systems, with solid evidence that synchronisation mechanisms underpin cognitive processes. Nevertheless, its informational content and relationship with behaviour are still to be fully understood. In addition, cognitive systems cannot be properly appreciated without taking into account brain–body–environment interactions. In this paper, we developed a model based on the Kuramoto Model of coupled phase oscillators to explore the role of neural synchronisation in the performance of a simulated robotic agent in two different minimally cognitive tasks. We show that there is a statistically significant difference in performance and evolvability depending on the synchronisation regime of the network. In both tasks, a combination of information flow and dynamical analyses show that networks with a definite, but not too strong, propensity for synchronisation are more able to reconﬁgure, to organise themselves functionally and to adapt to different behavioural conditions. The results highlight the asymmetry of information flow and its behavioural correspondence. Importantly, it also shows that neural synchronisation dynamics, when suitably ﬂexible and reconfigurable, can generate minimally cognitive embodied behaviour.

Keywords Synchronisation · Evolutionary robotics · Oscillatory networks · Transfer entropy · Kuramoto model

1 Introduction

Oscillatory neural activity is closely related to cognitive processes and behaviour (Engel et al. 2001; Buzsáki 2006). More specifically, it has been claimed that the flexible synchronisation of firing neurons is a fundamental brain mechanism (vonderMalsburg 1981; Singer 1993, 1999; Womelsdorf et al. 2007). Synchronisation may mediate the interactions between neurons and be an active mechanism of large-scale integration of neuronal assemblies, impacting on motor control and cognitive performance (Hatsopoulos et al. 1998; Varela et al. 1998; Varela et al. 2001; Jackson et al. 2003). Moreover, a range of pathological states are related to abnormal neuronal synchronisation regimes (Glass 2001; Brown 2003; Arthuis et al. 2009).

Whereas increasingly sophisticated computational and imaging techniques help us to observe and record from different physiological aspects of the nervous system, a great part of the challenge lies in the comprehension of this avalanche of data and its relationship with behaviour (Chialvo 2010). In addition, the brain presents spontaneous electrochemical activity that is constantly shaped by the body’s constraints and time-varying environmental stimuli (Katz 1999). The brain, therefore, not only processes information but also produces it, and cognitive phenomena are a product of brain–body–environment interactions (Stewart et al. 2010).

Situated artificial agents, in this sense, provide an appropriate experimental scenario to study the principles of intelligent behaviour (Boden 2006). There is a rich literature exploring the relationship between neural synchronisation and complex motor control in embodied (robotic) rhythmic behaviours (Taga 1994; Ijspeert et al. 2005; Pitti et al. 2009), where synchronisation
appears as a more intuitive underlying mechanism; however, to date there has been very little research on the wider issues of neuronal synchronisation in the generation of embodied cognitive behaviours. Therefore, using concepts from Evolutionary Robotics (Harvey et al. 2005; Floreano et al. 2008; Floreano and Mattiussi 2008; Floreano and Keller 2010), we explore the role of synchronisation in the performance of a simulated robotic agent during the execution of two different minimally cognitive tasks: the first, a categorical perception simulation of a robotic agent during the execution of two different tasks were chosen for being currently regarded as benchmarks in the evolutionary robotics and adaptive behaviour communities, with categorical perception underpinning cognitive systems (Harnad 1987).

The study reported here is intended to shed some light on the role of neural synchronisation in simple embodied cognitive behaviours. More specifically it aims to (1) test whether different degrees of coupling in the agent’s oscillatory neural network, which will encourage more or less synchrony in the network dynamics, have an effect on the performance of the agent and (2) determine if there are circumstances in which more (or less) synchrony is better suited to the generation of adaptive behaviour in the context of the tasks studied.

The neuronal model employed is based on the Kuramoto Model of coupled phase oscillators (Kuramoto 1984), which has been extensively studied in the Statistical Physics literature, with recent applications in a biological context due to its relatively simple and abstract mathematical formulation yet complex activity that can be exploited to clarify fundamental mechanisms of neuro-oscillatory phenomena without making too many a priori assumptions (Ermentrout and Kleinfeld 2001; Cumin and Unsworth 2007; Kitzbichler et al. 2009; Breakspear et al. 2010). The model explicitly captures the phase dynamics of units that alone have spontaneous oscillatory activity and once connected can generate emergent rhythmic patterns. Its synchronisation regime can be adjusted by one parameter (Strogatz 2000), suiting our study, whilst also avoiding any problems in obtaining phase information [an issue in other models which consider frequency and amplitude dynamics (Pikovsky et al. 2001)]. Phase relationships contain a great deal of information on the temporal structure of neural signals, are associated with cognition and relate to memory formation and retrieval (Li and Hopfield 1989; Izhikevich 1999; Varela et al. 2001; Kunyosi and Monteiro 2009). Furthermore, it has been shown that firing and bursting neurons can be modelled as oscillators (Murray 1989). Hence, the Kuramoto Model is highly relevant, at a certain level of abstraction, to modelling neural mechanisms underlying adaptive and cognitive behaviours.

Analysis of results is centred on how the information dynamics between the nodes of the network, the agent’s body and the environment vary depending on the current synchronisation status of the system and how this is reflected in the behaviour being displayed. Information Theory provides a framework for quantifying and emphasizing the nonlinear relationships between variables of the system, hence its suitability in Biology and Robotics studies (Rieke et al. 1997; Rolls and Treves 1998; Lungarella and Sporns 2006). In this context, agent-environment systems pose extra challenges in devising and interpreting a sensible measurement of information flow, for they normally have noisy and limited data samples, asymmetrical relationships among elements of the system and temporal variance (i.e. sensory and motor patterns may vary over time). Transfer Entropy (TE), in this scenario, is suggested as a suitable and robust information-theoretic tool (Lungarella et al. 2007b,a), and has also been applied to investigate real neural assemblies and other neuroscience problems (Borst and Theunissen 1999; Gourévitch and Eggermont 2007; Buehlmann and Deco 2010; McDonnell et al. 2011; Vicente et al. 2011); it will, thus, be used in our analysis.

The paper is organised as follows: the next section presents some theoretical background to the main concepts explored in this study: oscillators and synchronisation, focusing on the Kuramoto Model, evolutionary robotics (ER) and the two minimally cognitive tasks studied, and Information Theory in an agent-environment context, describing TE. We then present the methods adopted to develop the experiments and analysis, covering the ER framework, the details of the active categorical perception and orientation under normal and inverted vision tasks, a description of the genetic algorithm used to optimize the parameters of the system, and concluding with details of the time-series analysis using TE. Following this, we present the results, which show a difference in performance and behaviour depending on the synchronisation regime of the network, relating the observed sensorimotor strategies with the dynamics and the information flow of the system. The paper closes with a discussion on the results obtained and future work proposals.

2 Theoretical background

2.1 Oscillators, synchronisation and the Kuramoto model

In a study pioneered by Winfree (1980), the dynamics of a population of interacting limit-cycle oscillators have been approximated by a population of interacting phase oscillators, leading to a mean-field approximation model extensively explored by Kuramoto (1984). In his approach, the phase of each oscillator is determined by its natural frequency (drawn from some distribution) modulated according to a