Social Neuroeconomics : A dynamical systems perspective

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In this article we examine social neuroeconomics from a complex systems point of view, that is rooted in the theory and methods of informationally coupled self-organizing dynamical systems. Our contribution focuses on establishinng a theoretical perspective within which one can interpret experiments recently published in the field of neuroeconomics. We explain how the concepts and methods of coordination dynamics may impact future neuroeconomics research. We address the non-equivalence problem between different levels of analysis that has received little if no attention in neuroeconomics. We also discuss how coordination dynamics might provide novel routes to studying the relation between brain activity and decision-making. One should not reduce economics to physics, nor should one aim at providing a single framework for economics and neuroscience. Rather one should seek, in these fields, to define more clearly the various levels of description and their shared dynamics. This should help us to understand interactions between various levels of analysis in neuroeconomics.

metastability - emergence - self-organization - phase transitions - cognition - emotions

Neuroéconomie des interactions sociales : Une approche par les systèmes dynamiques

Dans cet article nous envisageons la neuroéconomie des interactions sociales du point de vue des systèmes complexes et de la théorie des systèmes dynamiques. Nous développons le problème de la non-équivalence entre les différents niveaux d'analyse qui n'a pas encore été abordé dans le cadre de la recherche en neuroéconomie. Ce problème se pose lorsque l'on désire intégrer dans un même cadre théorique et/ou méthodologique des données collectées à différentes échelles (du niveau individuel au

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niveau collectif) de description dans le cerveau ou dans la société. Enfin, nous illustrons comment la théorie des systèmes dynamiques pourrait offrir des voies originales dans la compréhension des relations entre l'activité cérébrale dynamique comportementale et prise de décision. Tout comme il ne serait pas opportun de réduire les sciences économiques à une approche basée exclusivement sur les sciences physiques, nous ne désirons pas développer un cadre théorique et expérimental unique pour les sciences économiques et les neurosciences. Nous cherchons plutôt à définir plus clairement les différentes échelles de description et à mettre en exergue leur dynamique partagée. Ainsi pourrons-nous comprendre les interactions entre des phénomènes se déroulant de manière concomitante à différents niveaux d'analyse.

métastabilité - émergence - coordination - transitions de phase - systèmes dynamiques - cognition

Classification JEL : D87, D81, D85, C91, C92

The body of experimental literature in *neuroeconomics* (or decision neuroscience, as some prefer to refer to it; e.g. Glimcher, [2003]; Sanfey, [2007]) is constituted of experiments that are performed at multiple levels of analysis with diverse methodologies ranging from methods allowing one to estimate metabolic activity in the brain (e.g. functional magnetic resonance imaging; fMRI), electrical activity (e.g. electro-encephalography; EEG) or even to alter temporarily the functioning of the brain (e.g. transcranial magnetic stimulation; TMS)[6]. If one tries to connect data collected at various levels of description, not only technical but also conceptual problems can emerge. For instance, one is facing the challenge of linking different levels of description (1) inside the brain, but also between (2) the brain and the body and (3) between the body and the physical and social environment in which it evolves (Fuchs et Jirsa [2008]). Reciprocal causality exists between the individual and collective levels but there are still open questions regarding the understanding and the modelling of such intra- and inter-level interactions (Kirman [1992]; Kelso et Engstrøm [2006]). It seems to us that a coherent framework both for the integration of data collected at various levels of analysis and for analyzing the dynamics of decision-making itself is still lacking. Of course such an issue pertains not only to neuroeconomics, but so far, it has received little if no attention in the literature dedicated to this new field of research. Motivated by converging hypotheses on the role of neural synchrony in the emergence of cognition we propose to discuss neuroeconomics in the context of nonlinear dynamics and self-organization (e.g. Bressler et Kelso [2001]; Uhlhaas et Singer [2006]; Kelso [1991, 2002]; Varela *et al.* [2001]). We do not claim to provide final answers to existing issues, but our goal is simply to give the readership a different way of looking at the behavioural and neural dynamics underlying the neuroscience of economic decisions and choice behaviour.

6. For more details on the main methods employed in neuroeconomics to estimate, record or alter brain activity see a technical and conceptual introduction by Charron and colleagues (this issue).

1. Coordination dynamics

The economy is a complex system whose aggregate behaviour is determined by an incredible number of co-existing interactions (more or less complex in nature) that occur at the individual level as well as between levels of description. It is therefore possible to draw analogies with physical, chemical and biological systems. Economic agents constantly interact with each other in many ways and for different purposes. Somehow, out of these individual interactions, certain coherent patterns of behaviour emerge at the aggregate level (Hayek [1952]; Kirman [1992]). Among all the elements that contribute to the emergence of collective patterns, information exchange might very well be the most important one. However macroscopic behaviour cannot be thought of as reflecting the behaviour of a "typical" or "average" individual. For instance, there is no simple direct correspondence between individual and aggregate (ir)regularity (see Debreu [1974]; Kirman, [1989, 1992, 1993]; Sonnenschein [1972]). In other words, the behaviour at the collective level may not be deduced, calculated or extrapolated simply from a linear aggregation of individual behaviour, whether in the brain or the society (Kelso [1995]; Lagarde et Bardy [2007]; Nowak *et al.* [2000]). As observed by Anderson [1972], the (collective) whole is not necessarily greater than the sum of the (individual) parts: *"More is different"*.

In spite of the absence of direct link between levels of analysis, it appears that coordination phenomena emerge so spontaneously and so consistently as to suggest the existence of an underlying structure or regularity that transcends the multitude of differences between the various situations analysed. Kelso and Engstrøm [2006] describe the following: (1) patterned states of coordination remaining stable over time despite perturbations, (2) the component parts and processes (dis)engaged in a flexible fashion depending on functional demands and/or environmental conditions change, (3) the existence of multiple coordination states, i.e. multi-functionality, effectively satisfying the same (or different) set of circumstances, (4) rapid selection of coordination patterns tailored to suit the current needs of the organism, (5) adaptation of coordination to changing internal and external contingencies, (6) abrupt transitions from one coordinated pattern to another, (7) transitions from partially to fully coordinated states (or vice-versa), (8) coordinative memory, i.e. remaining in the current pattern of coordination even when conditions change (Kelso [1995]).

Why should economic decision making be an exception? After all, a number of basic coordination phenomena exist that seem to cut across a wide range of levels, creatures and functions. There is now a wide consensus regarding the self-organized nature of the brain, where phase synchrony emerges when information is exchanged on various scales (Edelman [2004]; Kelso [1995]). In addition, recent advances in the brain and movement sciences have revealed the self-organized and informational nature of human behaviour and cognition (Bressler et Kelso [2001]; Kelso [1981; 1994]). Neuroeconomics, from this point of view could be conceived of as the *coordination dynamics of economic decision-making* and therefore be modelled as phase transitions (or bifurcations) from unstable to more stable cognitive states involving neurons and/or parts of the brain (see Oullier *et al.* [2008b] for a detailed treatment of this hypothesis). It is rather surprising that such a perspective has not (yet) been explored by neuroeconomists in spite of the nonlinear features exhibited by both brain and cognitive processes at multiple levels of description (Bressler et Kelso [2001]; Brown *et al.* [2005]; Edelman [2004]; Friston [1997]; Kelso [1995]; Oullier et Kelso [2006]).

A central problem of coordination dynamics on any level of observation is to identify the key variables of coordination and their dynamics, i.e. rules that govern the stability and change of coordination patterns. Basic forms of coordination emerge, not because of a special coordinating agent, but rather as a result of the system's ability to self-organize when open to information exchange with its environment. Indeed, the 'system' properly construed consists of both organisms and their environments, with full recognition of their co-evolution. Along with predictive mathematical modelling, coordination dynamics provides a new foundation for understanding coordinated behaviour grounded in the concepts of self-organization and the tools of nonlinear dynamics and especially tailored to handle the informational (e.g. perceptual, cognitive, affective) aspects of human behaviour (Kelso et Engstrøm [2006]; Kelso [1995]).

Whereas common principles of self-organization make it possible to describe the behaviour of both individuals and whole populations, whether neurons (Edelman [2004]; Hopfield [1982]; Kelso [1995]) or economic agents (Haerdle et Kirman [1994]; Kirman [1993, 1997]), most of the time it is not possible to establish direct unequivocal relationships between various levels of analysis.

2. Shared dynamics

A first way to look at the issue of non-equivalence between levels of analysis is through the lens of coordination dynamics, and the synchronization that emerges at different levels in the brain (Kelso [1995]; Pikovsky *et al.* [2001]; Strogatz [2003]; Varela *et al.* [2001]), between the brain and the environment (Kelso *et al.* [1998]) or between two bodies/brains (Oullier *et al.* [2005, 2008a]; Tognoli *et al.* [2007a,b]). Studies conducted within the framework of informationally coupled, self-organizing dynamical systems have employed coordination tasks as a means to uncover the link between the dynamics of behaviour and the dynamics of the brain, connecting these levels by virtue of their shared dynamical properties (e.g. Fuchs *et al.* [1992]; Kelso [2000]; Kelso *et al.* [1991, 1992]). The high temporal accuracy of electroencephalography (EEG) and magnetoencephalography (MEG) was exploited to quantify the relationship between behavioural and spatiotemporal patterns of neural activity. These data offer a conceptual link between the large scale neural dynamics emerging from billions of neurons (and their countless interconnections) and the behavioural dynamics revealed in experiments on coordination dynamics (Fuchs et Jirsa [2008]; Oullier et Jantzen [2008]). Common features of the dynamics expressed at both levels of description, including *phase transitions* (*i.e.* the spontaneous switch from one pattern to another), were taken as evidence that similar principles of self-organization govern pattern formation in brain and behaviour. Of particular initial interest was the identification of qualitative changes in the pattern of neural activity that occurred simultaneously with transitions between behavioural coordination patterns (Fuchs *et al.* [1992]; Kelso *et al.* [1991, 1992]).

These findings could shed new light on more recent work in the domain of social interactions that may provide new perspectives in social neuroeconomics (Fehr et Camerer [2007]) as illustrated by a series of experiments on social coordination dynamics performed at the *Center for Complex Systems and Brain Sciences.* Tognoli and colleagues [2007a] identified new neural mechanisms underlying social interactions that (dis)appeared at the same time as their behavioural correlates. Using the coordination dynamics framework, they investigated how social processes are integrated in the brain using a specially designed dual-electroencephalogram system (dual-EEG)[7]. This study follows on of previous work at the behavioural level that reported for the first time a real-time quantification of the level of bonding between people during and after social encounters. A precise measure of interpersonal coordination not only during the social interaction but also after[8] was explored (Oullier *et al.* [2005, 2008a]).

The neural signatures identified for the first time by Tognoli and colleagues [2007a] are referred to as *neuromarkers of social coordination,* that (dis)appeared with the emergence/dissolution of coordinated behaviour between individuals. These so-called neuromarkers are brain rhythms in the 10 Hz frequency range located over the right centro-parietal cortex. They clearly distinguished uncoordinated interpersonal coordination from synchronization that emerged spontaneously. Termed the *Phi Complex* by the authors, these neuromarkers consist of two components. The first, Phi_1, increased during independent behaviour, i.e. before information was exchanged between the members of the dyad. When information was exchanged Phi_1 disappeared and Phi_2, a different rhythm within the same band, appeared only during social coordination (Tognoli *et al.* [2007a]).

In a subsequent study, Tognoli and colleagues [2007b] explored the dynamics of the Phi Complex when instructions in the SCD paradigm were slightly changed. They asked participants to intentionally coordinate when information exchange was allowed. Again, Phi_1 appeared during the uncoordinated behaviour and Phi_2 when social coordination occurred. Thanks to dyads that participated in both neural experiments (Tognoli *et al.* [2007a, b]), there is an indication that the magnitude of Phi_2 was higher when people coordinated intentionally.

The fact that such concomitant effects occur in the brain and between individuals offers another illustration of the shared dynamics between levels

7. Each participant therefore wore a 60-channel EEG-cap allowing for simultaneously recording brain dynamics of two persons on the same time scale as their behaviour.
8. The so-called *social memory* effect, i.e. the degree to which individuals remain influenced by each other after a social encounter is over (Oullier *et al.* [2008a]).

and how coordination dynamics may help to bridge the gaps between levels them. Tognoli and colleagues [2007a,b] open new perspectives by providing potential insights on whether transitions from uncoordinated to coordinated previously reported at the behavioural level are accompanied by similar events at the brain level by virtue of shared neural and behavioural social coordination dynamics (see Oullier et Kelso [2009] for a review). Such a result might be of great relevance in social neuroeconomics when studying the neural correlates of individuals participating in coordination games. The presence of Phi_2 might indicate whether people coordinate or not and its magnitude might distinguish cooperation from competition in economical exchanges involving multiple agents.

3. Phase transitions and economic decisions

The experiments described (Fuchs *et al.* [1992]; Kelso *et al.* [1991; 1992]; Tognoli *et al.* [2007a, b]) hint at the potential for considering decision-making dynamics at the behavioural and neurophysiological levels in a common dynamical systems perspective. Hence, the theoretical framework adopted could serve as an interesting entry point to addressing the issue of non-equivalence between levels of analysis in neuroeconomics (Oullier *et al.* [2008b]). In order to do so, one could model decision-making as a system which tends to functionally explore the patterns that can be adopted in the vicinity of the (phase) transition between "decision-preparing" and decision-making. In this "preparation region", the system can adopt potentially either pattern. This would suggest the representation of a kind of dynamic *multi-stablity* among choice alternatives.

A very interesting contribution in this direction can be found in Roxin et Ledberg [2008] who have managed to reduce nonlinear neural networks models to a single nonlinear diffusion equation. By varying external inputs, they provide one of the rare connections between behavioural and neurophysiological dynamic decision-making, modelled as a pitchfork bifurcation. Roxin and Ledberg's work should thus be of great interest for the neuroeconomics community. The same is also true of advances in the neurodynamics field by Loh and colleagues who stress the key role of attractor dynamics in a network of interconnected neurons involved in generating a cognitive process (cf. Loh *et al.* [2007]). They argue in favour of considering the stability of a given pattern within its basin of attraction and suggest that the depth of the basin of attraction could be modulated by high neuronal firing rates and strong synaptic connections between neurons. Hence, the attractor state may be more resistant to distraction by a different stimulus. They also explored the dynamics of the prefrontal cortex in cognitive tasks in which stimuli have to be associated with actions by trial-and-error learning (Loh *et al.* [2007]). Loh and colleagues revealed that, in such a context, the dynamics of the prefrontal cortex is bistable, yielding distinct activations for correct and error trials. Although not obtained in the context of economic decision making, Loh *et al.*'s results could be of great interest in neuroeconomics. For example, they could help disentangling the inner dynamics of the prefrontal cortex in the ultimatum game in the context of experiments revealing that inhibition or dysfunction of different parts of the prefrontal cortex led to opposite economical decisions (see Knoch *et al.* [2006]; Koenigs et Tranel [2007]).

Local dynamics are not the only relevant thing here, since synchronous neural oscillations have been identified in specific parts of the brain (Singer [1999]) as well as at larger scales, i.e. between distant cortical structures (Başar [2004]; Kelso [1995]; Varela *et al.* [2001]; von Stein et Sarnthein [2000]). Also of interest, are the low frequency oscillations (< 0.08 Hz) between brain areas that allow for a measure of what is referred to as *functional connectivity* (Friston *et al.* [1993]). Various studies have revealed the existence of residual variable fluctuations in cerebral activity that appear to be synchronized, in different brain locations. These fluctuations are low frequency oscillations that are an intrinsic property of the symmetrical cortices and have been found in various areas of the brain (e.g. Biswal, *et al.* [1995]). Such fluctuations corroborate the existence of functional connectivity, i.e a descriptive measurement of the space-time correlations between distinct areas of the cerebral cortex (Friston *et al.* [1993]). The functional connectivity of low frequencies is a good indication of neuronal regulation in the brain. Computing functional connectivity offers a significant advantage over more traditional fMRI analysis. Indeed, this method not only makes it possible to identify the brain areas that are functionally dependent but also the directions of the influences between these areas. When a cerebral network underlying an economic decision is identified, the issue of directionality of influence within the network is crucial. Understanding directionality will also allow a deeper understanding of the interplay between brain, the areas involved in cognition and emotion.

Among the many approaches that can be used to compute functional connectivity (cf. Kirsch *et al.* [2005]), one is of particular interest in our theoretical framework as it is based on *self-organizing map* algorithms (SOM; Peltier *et al.* [2003]). This technique makes it possible to compare areas pairwise without having to use a reference function or to define specific areas of interest. For example, if one takes the results of the fMRI version of the ultimatum game (Sanfey *et al.* [2003]), a functional connectivity analysis might help to provide more accurate information regarding the exchanges between the DLPFC and the insula, such as what the temporal sequence of these interactions is.

4. The metastable brain

Context-dependent synchronization of oscillatory neuronal responses has been observed within and between various areas of the brain illustrating how it can function simultaneously in an integrated and in a segregated fashion. This property is known as *metastability*. A novel aspect of coordination dynamics is that where stable states of coordination do not occur, a more subtle metastable régime exists (Kelso [1995]; Edelman [2004]; Friston [1997]). Metastability is characterized by partially coordinated tendencies in which individual coordinating elements are neither completely independent (local segregation) nor fully linked in a fixed mutual relationship (global integration) as is the case in the binding problem (Gray [1999]; Roskies [1999]). Thus, the two polar tendencies of specialized brain regions, to express their autonomy and to work together as a coherent unit co-exist simultaneously. Considering that one's physical and social environments and state of mind are subject to rapid and often unpredictable change during the decision-making process, the brain must be able to exhibit adaptive features on a fast timescale. By virtue of a subtle balance between the intrinsic neuronal properties of individual brain areas and the synaptic coupling between them, metastability provides a mechanism for task-relevant brain areas to engage and disengage flexibly to accomplish real-time information processing and decision–making. The essentially nonlinear dynamics also permits rapid switching between different brain synergies through the reorganization of component areas into different coordinated behavioural and brain networks (Friston [1997]; Kelso [1995]).

Such a vision is highly suggestive for the economist and allows one to envisage the economy or market as a collection of networks each of which is closely interconnected. These in turn are linked but the link between them may be used less intensively and less frequently. This somehow echoes the design of "small world" networks (Watts [1999]).

It has recently been suggested that neuroeconomics should build upon the strengths of the 'unitary perspective' in economics and the 'multiple-systems approach' in neuroscience to challenge classic decision-making theories rooted in rationality (Sanfey *et al.* [2006]). In an attempt to bridge the conceptual gap between neuroscience and economics an analogy between the *modus operandi* of the brain and of a corporation has been proposed. Both are presented as systems ruled by an executive control that interacts with more or less independent specialized agents that transform an input into an output (Sanfey *et al.* [2006]). This principal multi-agent view might be right but tells us little about how levels are linked and how information is exchanged within and between those levels.

An alternative approach to this purely hierarchical model is coordination dynamics (Kelso [1995]). Inspired by self-organizing principles specifically tailored to the informational demands of cognitive and brain function, coordination dynamics proposes that coordination patterns may spontaneously arise from nonlinear coupling among interacting components. Which patterns arise and which resultant decisions are made depend upon the stability of the system under given constraints. As circumstances change, one pattern may lose stability and another emerge spontaneously because it better fits the current demands of the situation. Such context-dependent decision-making has been observed at both behavioural and cerebral levels and could therefore provide at least some answers to the problem of integrating data from neuroeconomics experiments within a unified theoretical framework. As a conceptual framework for spontaneous decision-making that respects the dynamics of both the brain and the economy, metastability could become a central concept in the development of the transdisciplinary field of neuroeconomics.

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