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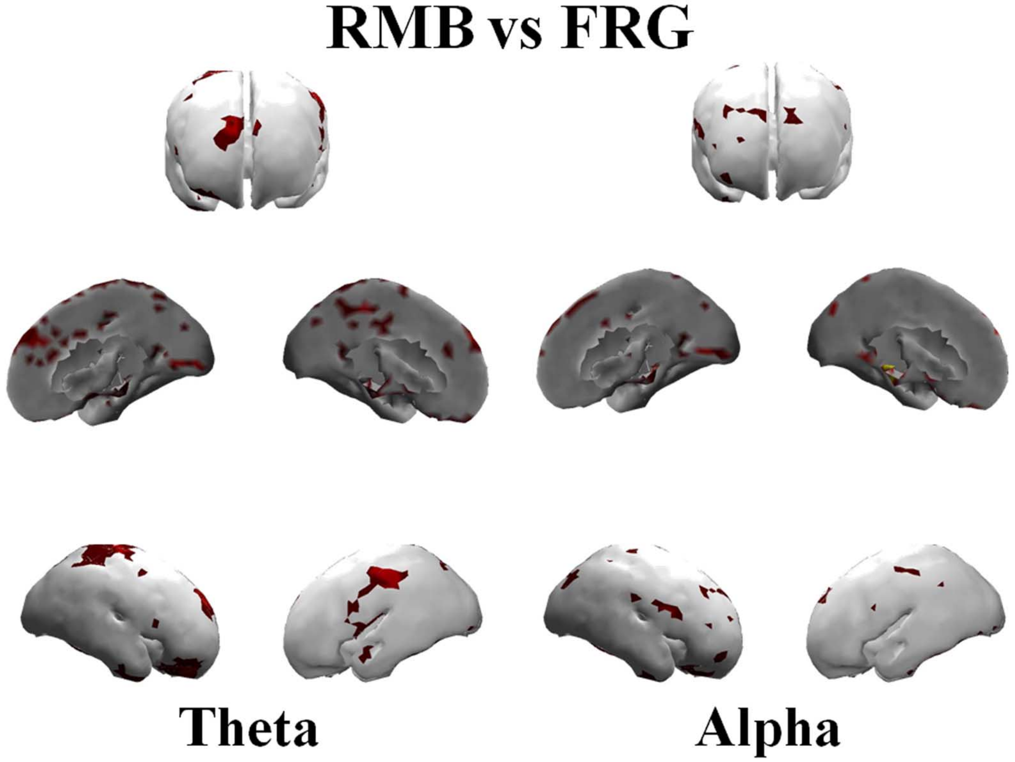

Figure presents the results of the statistical comparisons between the RMB and the FRG dataset in the Theta and Alpha frequency bands, as described in the paper "Neural Basis for Brain Responses to TV Commercials: A High-Resolution EEG Study" by L. Astolfi, F. De Vico Fallani, F. Cincotti, D. Mattia, L. Bianchi, M. G. Marciani, S. Salinari, A. Colosimo, A. Tocci, R. Soranzo, and F. Babiloni on page 522.

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## SPECIAL SECTION ON NEUROECONOMICS

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# Guest Editorial
# Neuroeconomics: A Neural Engineering Perspective

THE question of how we make, and how we should make, judgments and decisions has occupied thinkers for many centuries, with different disciplines approaching the problem with characteristically different techniques. A very recent approach, known as neuroeconomics, has the goal to integrate ideas from the fields of psychology, neuroscience, and economics in an effort to specify more accurate models of choice and decision. This special issue of "Neuroeconomics: Modeling and imaging the brain activity during economic transactions" is trying to include both the state-of-technique papers on the methodologies and models that it can be used in this field on humans. The scenario that comes out from the series of papers chosen from active authors in this new area of science is really interesting. From one side, there is the development of methodologies that allows estimate the brain activity during decision making tasks by using hemodynamic [1] or electromagnetic modalities [2], [3]. On the other side, there are contributions about theoretical [4] and practical aspects [5] of the application of neural engineering to the neuroeconomics.

In particular, the paper of Grosenik *et al.* [1] faced with the attempt to classify sensory inputs in order to directly predict the behavioral output, by using the hemodynamic information related to the brain activity. They applied different machine learning algorithms to previously acquired data to examine the ability of functional magnetic resonance imaging (fMRI) activation in three regions—the nucleus accumbens (NAcc), medial prefrontal cortex (MPFC), and insula—to predict purchasing. Their goal was to improve spatiotemporal interpretability as well as classification accuracy. The use of electroencephalographic data was instead promoted in the context of prediction of particular memorization of TV advertising in the paper of Astolfi *et al.* [2]. There, the signs of brain activity related to the observation of TV ads were detected by using advanced statistical techniques. The techniques presented here shed new light on all the cortical networks and their behavior during the memorization of TV commercials. Such techniques could also be relevant in neuroeconomics and neuromarketing for the investigation of the neural substrates subserving other decision making and recognition task. The use of EEG technology was also promoted in the paper of Bordaud *et al.* [3] for the study of the correlates of the brain electrical activity related to the exploratory behavior. In fact, decision making in an uncertain environment arises a conflict between two opposing needs: gathering information about the environment and exploiting this knowledge in order to optimize the decision. Authors generate a model of how the subject behaves while making his decision, and suggested EEG processing methods able to handle signals that can shift in time across trials due to the nature of exploratory behavior. The paper of Oullier *et al.* [4] illustrates a theoretical perspective for the interpretation of experiments recently published in the field of neuroeconomics and addresses how the concepts and methods of coordination dynamics may impact future research in that field. The starting point of this paper is the concept of the basic reciprocity between individual parts and collective organization that constitutes a key scientific question spanning the biological and social sciences. The paper addresses the problem of understanding the nature of the interactions and coordination dynamics between individual (neuron $\sim$ agent) and collective (neural networks $\sim$ population of humans) behaviors in the growing field of neuroeconomics. The contribution of Kenning and Plassman [5] has a theoretical nature and would like to provide an overview of questions of interest to consumer researchers, to present initial research findings, and to outline potential implications for consumer research. The paper concludes with a discussion of potential implications and suggestions for future research in the nascent field of consumer neuroscience. We hope these papers could be useful for orienting your research in this new scientific area.

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IEEE TRANSACTIONS ON NEURAL SYSTEMS AND REHABILITATION ENGINEERING, VOL. 16, NO. 6, DECEMBER 2008

# The Coordination Dynamics of Economic Decision Making: A Multilevel Approach to Social Neuroeconomics

Olivier Oullier, Alan P. Kirman, and J. A. Scott Kelso

***Abstract*—The basic reciprocity between individual parts and collective organization constitutes a key scientific question spanning the biological and social sciences. Such reciprocity is accompanied by the absence of direct linkages between levels of description giving rise to what is often referred to as the *aggregation* or *nonequivalence problem* between levels of analysis. This issue is encountered both in neuroscience and economics. So far, in spite of being identified and extensively discussed in various (other) scientific fields, the problem of understanding the nature of the interactions and coordination dynamics between individual (neuron ~ agent) and collective (neural networks ~ population of humans) behaviors has received little, if any attention in the growing field of *neuroeconomics*. The present contribution focuses on bringing a theoretical perspective to the interpretation of experiments recently published in this field and addressing how the concepts and methods of *coordination dynamics* may impact future research. First, we very briefly discuss the links between biology and economics. Second, we address the nonequivalence problem between different levels of analysis and the concept of *reciprocal causality*. Third, neuroeconomics studies that investigate the neural underpinnings of social decision making in the context of two economic games (trust and ultimatum) are reviewed to highlight issues that arise when experimental results exist at multiple scales of observation and description. Finally, in the last two sections, we discuss how coordination dynamics might provide novel routes to studying and modelling the relation between brain activity and decision making.**

***Index Terms*—Complex systems, information exchange, interpersonal synchronization, nonlinear dynamics, phase transition.**

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## I. Introduction

> "The problem of a rational economic order is determined precisely by the fact that the knowledge of the circumstances of which we make use never exists in concentrated or integrated form, but solely as the dispersed bits of incomplete and frequently contradictory knowledge which all the separate individuals possess. The problem is thus in no way solved if one can show that all of the facts, if they were known in a single mind (as we hypothetically assume them to be given to the observing economist), would uniquely determine the solution; instead we must show how a solution is produced by the interactions of people each of whom possesses only partial knowledge."

Friedrich Hayek [63]

COORDINATION comes in many guises and represents one of the most striking, but least understood features of living organisms. Defined as a functional ordering among interacting components in space and time, coordination achieves its pinnacle in the vast array of cells and connections called the human brain, and in the collection of human beings we call society [81], [88]. How coordination forms and changes in such complex systems is of great interest to many disciplines, particularly psychology, neuroscience, biology, physics, and economics. The basic reciprocity between individual parts and collective organization constitutes one of the key scientific questions spanning the biological and social sciences. Such reciprocity is accompanied by the absence of direct linkages between levels of description giving rise to what is often referred to as the *nonequivalence problem* between levels of analysis. This problem is encountered both in neuroscience (e.g., [9], [24], [81], [171]) as well as in economics (e.g., [96], [147]). So far, in spite of being identified and extensively discussed in various (other) scientific fields, the problem of understanding the nature of the interactions and coordination between individual (neuron ~ agent) and collective (neural networks ~ population of humans) behaviors has received little, if any attention in the growing field of neuroeconomics. At the very least, the levels (individual ~ collective), or *aggregation problem* as it is frequently described in economics, begs an answer to three complementary questions.

- Is the knowledge of how a single neuron or agent behaves necessary to predict the dynamics of an assembly of neurons—agents that participates in economic decision making?

- Are the same principles of self organization observed at different levels of analysis even though the links and interactions between levels are unclear?
- How can we capture the activity of millions of neurons—agents for a cognitive process as complex as a decision made in the context of social economic exchanges?

Although we do not claim to provide definitive answers to these questions, our intention is to discuss them *via* a complex systems approach that is rooted in the theory and methods of informationally coupled self-organizing dynamical systems, *coordination dynamics* for short [81]. In coordination dynamics, the word information is not a throwaway. Rather, information is meaningful and specific to the dynamics and the forms it takes. In living things, the coordination dynamics are invariably functional and context dependent often spanning both the organism and the environment. In contrast to other theories of self organization, the order parameters in coordination dynamics are informationally meaningful. Likewise, stabilities in such a self-organizing system pertain to the stability of informationally meaningful quantities [80].

The present contribution focuses on 1) bringing a theoretical perspective to the interpretation of experiments recently published in the field of social neuroeconomics and 2) addressing how the concepts and methods of coordination dynamics may impact future neuroeconomics research. Our paper is therefore organized as follows.

First, we provide a brief background on the links between biology and economics and how the field of neuroeconomics has emerged. Second, we address the nonequivalence problem between different levels of analysis and the concept of *reciprocal causality*. Third, neuroeconomics studies that investigate the neural underpinnings of social decision making in the context of two economic games (trust and ultimatum) are briefly reviewed for this purpose. The aim of such descriptions is to highlight issues that arise when experimental results exist at multiple levels or scales of observation and description. Some logical (perhaps neuroscience-independent) questions that arise when one tries to interpret neuroeconomics findings in terms of multiple levels within a common theoretical framework are introduced. The intent here is not to swamp the (economics) readership of the journal with neurobiological details but to communicate the bigger picture behind our arguments.

Finally, in the last two sections, we discuss how coordination dynamics might provide novel routes to studying and modelling the relation between brain activity and decision making. Just as one should not want to reduce economics to physics, the aim is not to reduce economics and neuroscience to a single common framework, but rather to define the various levels of description more clearly and to understand the conditions that may allow one to pass from one level to another.

## II. ON THE BIOLOGICAL FEATURES OF ECONOMICS

Economics, for a brief period at the end of the 19th Century, was divided between using an approach based on physics (see [113] for a historical treatment) and one rooted in biology. Indeed, as economist Thorstein Veblen claimed in 1898: *"Economics, properly understood, is simply a branch of biology"* (cited in [172]). What we have experienced in economics, until very recently, is the triumph of an approach rooted in physics transformed by Arrow and Debreu [4] into an axiomatic mathematical one (see [170] for a discussion). Economists have based their analysis of economic behavior on a self-contained consistent theory of the rational individual—referred to as *homo œconomicus* [125].[1] As Jevons remarked, since there was no hope of looking into people's minds at that point in time, the only recourse was to make inferences about the way they behave [111].[2] These assumptions, though developed and refined over more than a century are, as Pareto himself and later Robbins, Hicks, Koopmans, and many other distinguished economists have discussed, based purely on the introspection of economists. In principle, choices could be observed, but individual choices were assimilated to individual preferences which were, nevertheless, unobservable. The foundation of economic behavior rested on what one chose. What one chose was what one preferred and that was the end of it. Simple axioms of consistency in choices were shown by Houthakker [68] and Uzawa [162] to be equivalent to abstract assumptions about preferences, apparently rescuing the empirical verifiability of economic behavior. Two major stumbling blocks remained. First, from a purely logical point of view, one cannot directly verify the consistency of empirical choices since these choices are not made simultaneously, as they would have to be in order to be consistent with economic theory. Second, if one abstracts from experiments that present people with choices, one often finds that subjects do not always make "consistent" choices, in the sense that the choices that they actually make violate the standard axioms [19]. It is here that Veblen's apparently provocative assertion reveals its full force for it anticipated the advent of *neuroeconomics* [52].

Simply put, neuroeconomics is an interdisciplinary field of research that aims at uncovering the neural substrates underlying economic decision making. Neuroeconomics sheds new light on why discrepancies can be found between behavioral experiments performed in the laboratory, behavior observed in real-life situations, and standard economic theory, in particular the models based on that theory [19]. Neuroeconomics can therefore be seen as the next step in a path—constructed upon concepts from evolutionary psychology and biology as well as cognitive science [32], [60]–that links previous *bioeconomics* and *behavioral economics* approaches to human decision making [17], [51], [66]. As Paul Zak [172] observed: "*Whereas bioeconomics has focused primarily on ultimate causes of behaviour and behavioural economics has focused on how our evolved psychologies affect decisions, the neuroeconomics research programme seeks to discover proximate causes of choice behaviour*" (but see [167] for an alternate view).

Seen from a different, although complementary, angle Veblen's assertion on the biological origins of economics was also prophetic in a way which went beyond some simple scientific convergence between the brain and economic sciences. Behind it, one can also see the growing desire to explain, justify and root

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[1] To be fair to Pareto, it should be observed that in his later work he devoted a lot of his analysis to "irrational" behavior, that is to behavior which was not consistent with the standard assumptions about preferences [97].

[2] Now, with the advent of technology, we can look into the way the parts of the brain behave. Their relation to mind remains a bit of a mystery [84].

human behavior within biological science. Such a tendency generally accompanies attempts to merge behavioral and biomedical sciences. This has been the case with genetics, among other fields, and is currently happening with neuroscience.[3] As far as neuroeconomics is concerned, this tendency is illustrated by the willingness, or even desire, to naturalize decision-making processes. Promises (and sometimes fantasies) provided by neuroimaging techniques to access the so-called "emotional parts of the brain" involved in decision making often come with a strong reductionism, namely the repeated attempts to localize different economic activities in the brain. One can consider this a kind of "*econo-phrenology.*" The quest for decision making related areas or economically correlated neuronal activity (e.g., utility) has replaced the search for psychological bumps[4] [161]. If neuroscience can bring relevant information to economists it is not going to be found solely in the workings of the brain *per se* via elaborate (neuro)images correlated with decisional processes but also by taking into account the broader context within which the central nervous system works. A brain on its own (i.e., without interactions) would be useless [119]. Vital interactions occur both at the *intrinsic*, i.e., structural and functional connectivity between different parts of the brain and the body's regulatory systems, and *extrinsic* levels, i.e., between the brain and the physical, biological and social environments in which it evolves [22], [34], [64], [88]. Typically only the former aspect is emphasized, a point noted by the psychologist William Mace in the terse phrase: "*Ask not what is inside the head but what the head is inside of*" [112]. Little did he know that, 30 years later, his concerns would still be current and his advice echoed by many (intentionally or not), including Henry Greely: *"Human society is the society of human brains. Of course, those brains are encased in, affected by, and dependent on the rest of the body, but our most important interactions are with other people's brains, as manifested through their bodies"* [55].

Experiments in behavioral economics remind us, as if need be, that the neo-classical *homo œconomicus* does not correspond to what we observe in real life situations [93]. To make decisions, supposedly rational human beings should 1) process information that is diverse in origin and in nature and determine which actions are feasible, 2) evaluate in a rational way the consequences of each action that is feasible and, finally, 3) choose action(s) the consequences of which will provide the greatest "utility." Such a logical and rational approach to decision making is the inheritance of the marginalist revolution in economics (and the underlying assumption that the human brain works as a computer transforming inputs (information) into outputs (choices) in a sequential fashion; see [22], [23], [44]). Neo-classical theorists have developed a mathematically coherent theoretical framework based on the belief that human behavior can be described as an effort to maximize utility. In reaction to this, a number of economists (e.g., Allais [2] and Ellsberg [36]) have provided a wealth of analysis and evidence indicating that humans are not very efficient in maximizing utility, or put alternatively, they make choices which seem to violate the standard rationality axioms. This has led to alternate approaches that bring into question the postulates of the neo-classical revolution. Rational decisions, those which consistently maximize some underlying utility function with standard properties, are typically made only under certain quite precise conditions, the definition of which is crucial in understanding human behavior [144]. For example, given that parameters like *risk* and *uncertainty* were often neglected, standard utility theory has had to be modified to account for human decisions where these are present [76], [138]. Neuroeconomics brings with it the hope of being able to resolve (at least partially) those issues by recording cerebral activity to better understand the neurobiology underlying decision making processes, including the contributions of brain regions involved in emotions [53].

Thus, within the last decade, neural correlates of a broad range of complex behaviorally related phenomena and cognitive processes such as *reward* [62], *utility* [134]–expected [101] or marginal [155]–*regret* [26], decisions in moral dilemma [56], [154], *fairness* [137], *altruistic punishment* [28], and *trust* [173] to name only a few, have been uncovered using a variety of stimulation and brain imaging methodologies (see [21] for a review and a detailed analysis of the advantages and limits of these techniques in the context of neuroeconomics). Such discoveries contribute to advancing theoretical reflection and understanding of the dynamics of decision making. However, when unequivocal links are made between a few cubic millimetres of cerebral matter and a process as complex as economic decision making the ghost of reductionism rears its head.[5]

## III. NONEQUIVALENCE BETWEEN LEVELS OF ANALYSIS AND CIRCULAR CAUSALITY

Although, as we have mentioned, there has been a tendency to take shortcuts between "cerebral flashing blobs" and decision making, the present focus is on a theoretical problem common to both disciplines: the difficulty of identifying and understanding the nature of the coordination between the various levels of description and/or analysis.

*How do the myriad disparate individual economic and/or neuronal activities come to be coordinated?*

A central problem of coordination dynamics at any level of observation is to identify the key variables of coordination and their dynamics, i.e., rules that govern the stability and change

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[3] Readers interested in this topic might wish to look at contributions by geneticist Axel Khan and apoptosis expert Jean-Claude Ameisen in the *Comité Consultatif National d'Ethique pour les Sciences de la Vie et de la Santé*'s [National Consultative Ethics Committee for Life and Health Sciences] report published in 2007 [25].

[4] In the 19th Century, phrenology was a very popular technique to determine one's psychological features by feeling and measuring bumps in the skull. German physician Franz Joseph Gall (1758–1828) is considered the founding father of phrenology in the early 1800s. Nowadays, people refer to neo-phrenology when, in light of neuroimaging experiments complex actions or behaviors are attributed to a given area of the brain and/or when the same area of the brain is claimed to be involved in two different actions depending on the theoretical framework of investigation [161].

[5] Much of the time, such thinking emanates not from the scientists themselves, but from people who, for political and/or financial motives, attempt to transfer experimental results from the laboratory to real life situations as if there were context-independent relations between brain activation and decisions [70] In addition, until recently the predominant data processing methodology used in functional MRI "subtracted" brain activity in one condition from another favoring attribution of cause to particular brain regions (but see [45]). In any case, great caution needs to be exercised in the move from laboratory experiments (and their interpretation) to practice in real world settings, such as marketing or courts of justice to mention only two that have received extensive media coverage [119]

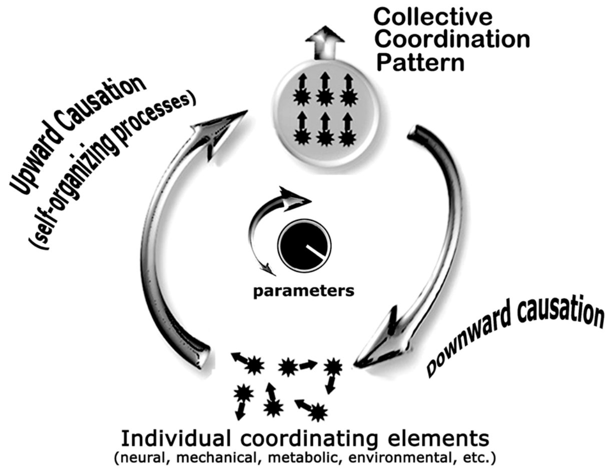

Fig. 1. Reciprocal causality of coordination dynamics (adapted from [88]).

of coordination patterns. Basic forms of coordination emerge, not (or not only, as often assumed) 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 [81], [88]. Along with predictive mathematical modelling, coordination dynamics provides a foundation for understanding coordinated behavior in living things [85]. Coordination dynamics is grounded in the concepts of self organization and the tools of nonlinear dynamics. It differs from yet complements related approaches such as *synergetics* and *dissipative structures* [59], [116] in that it is especially tailored to handle the informational (e.g., perceptual, cognitive, affective, etc.) aspects of human behavior [81]. Whereas common principles of self organization make it possible to describe the behavior of both individuals and whole populations, whether neurons [34], [67], [81], or economic agents [58], [94], [95], most of the time it is not possible to establish direct unequivocal relationships between various levels of analysis. In other words, the behavior at the collective level may not be deduced, calculated or extrapolated simply from the sum, the average or any other statistical computation of individual behavior, whether brain or society [117].

Hence, information coming from at least three (relative) levels is necessary to understand how self-organized patterns arise: 1) the level of the constraints and the parameters acting as boundary conditions on the coordination patterns that can emerge, 2) the level of the individual components each having their own intrinsic dynamics, and 3) the level of the pattern itself (Fig. 1). As described by Kelso and Engstrøm [88]: "*collective coordination patterns arise from the interaction among variable subsystems and processes yet reciprocally constrain the behaviour of these coordinating elements,*" a feature they coined *reciprocal causality of coordination dynamics*. Hence, the (collective) whole is not only greater than the sum of the (individual) parts, it happens to be different too [3].

With respect to economic decision making, it is easy to think of the economy as a complex system whose aggregate behavior is determined by complicated interactions at the individual level as well as across levels. The analogies with physical, chemical, and biological systems are obvious. Economic agents constantly interact with each other in different ways and for different purposes. Somehow, out of these individual interactions, certain coherent patterns of behavior emerge at the aggregate level. *Information exchange* is crucial in those interactions. However macroscopic behaviors cannot be thought of as reflecting the behavior of a "typical" or "average" individual [165]. There is no simple direct correspondence between individual and aggregate regularity [29], [92], [94], [148]. Neuroeconomics is not immune to these issues: data are collected at multiple levels of description without necessarily considering how levels are linked. Moreover, the very definition of a level in the first place is not a given; it is usually the scientist's prerogative to choose a level of description. In addition, neuroeconomics not only has to link different levels of description within the brain, the body and the environmental circumstances that act upon them, but also between the brain and the behavior of an individual as well as between the individual and the aggregation of individuals in a society.

To illustrate the difficulty in linking levels together into a coherent framework, in the following section, we present a brief overview of recent experiments which have explored the neural underpinnings of monetary exchange involving social trust and fairness at various levels of description.

## IV. SOCIAL NEUROECONOMICS AT VARIOUS LEVELS

Combining the concepts and methods of *neuroscience* (e.g., neurophysiological measures, brain imaging) and *game theory* (e.g., economic games) provides an opportunity to investigate the processes underlying social interactions as well as economic exchanges between two (or more) individuals. Over the past decade cognitive neuroscientists interested in the neural foundations of social interactions have studied topics such as trust, altruism, and punishment to name only a few. In doing so, they have noted and used the considerable body of results coming from well-controlled experimental paradigms in game theory [17]. The contribution of game theory to economics is that it allows one to consider direct interactions between agents when they make economic decisions. Game theory appears to be in contradiction with the standard economic paradigm in which people do not interact directly with each other but only indirectly through prices. In other words, game theory takes the opposite position to the neo-classical assumption that there is no direct information exchange between agents.

It is noteworthy that for many scientists working in the social and brain sciences the basic economic hypothesis that individuals act in isolation might seem surprising, to say the least. The counterpart of this improvement with respect to previous (unrealistic) theories in economics, is that game theory relies on strong hypotheses regarding the agents' rationality. For instance, it is assumed that agents make choices using primarily rational cognitive resources based on logic and individual maximization. Much more than this, the players take account of the reactions of other players and worse, attribute the same sort of reasoning to those players. This leads to logical problems such as the well-known "common knowledge" paradox. The "players" in game theory therefore resemble more the early game theorists than their more emotional or "behavioral" peers. Hence, what was originally intended to offer a more realistic description of economic reality became essentially an abstract modelling technique. This is why, paradoxically, experimental economics has had to take a step back to progress and to focus on the rationality effectively exhibited by the agents (or its absence) in order to obtain a more realistic view of the way in which they make their decisions when interacting with their peers. Theoretical models could, as a result, be confronted with and enlightened by empirical data. This is where neuroscience and the potential opportunities to distinguish rational processes from emotional reactions in decision making (which might be impossible after all) turned out to be interesting for game theorists and gave rise to *social neuroeconomics* [38], [135]. In social neuroeconomics experiments, participants play economic games in various contexts while their brain activity is recorded and/or their behavior is affected by the use of neuroactive substances such as neuropeptides. Here we will focus on two of the most explored experimental paradigms in game theory: the trust and ultimatum games.

Several research teams have studied cerebral activity when participants play a *trust game* [8], [18]. In this game, the first player is the *investor*. At the beginning of the game, the investor owns a certain amount of money. During the game, he will be able to give part (or all) of his money to the second player: the *trustee*. The money the investor decides to share is multiplied by a factor $n$ before the trustee receives it. Thus, if the investor gives \$10 and $n = 3$, therefore the trustee ends up with \$30. Then, the latter is free to give back (or not) to the investor a part of the money he received. Typically, the game consists of multiple rounds so that the investor and the trustee's behaviors evolve depending on how each reacts to the other, thereby allowing for interpersonal "trust" to develop or not. Thus, if the trustee returns a share that the investor considers a breach in trust, it is unlikely that the investor will give a lot of money in subsequent rounds. During this game, the investor is therefore confronted with a *social dilemma*. Trusting the person to whom the money is given can turn very profitable since, in theory, it is in both players' interest to trust each other and send each other large amounts of money to make more profits. At the same time, the investor exposes himself to a clear risk if the other player decides to breach trust and free ride [30]. An important aspect of this game is that it is repeated. In such games cooperative behavior can be sustained as an equilibrium since a breach of trust can be punished. However, if the number of periods in the game is known, there is no possibility of punishment for bad behavior in the last round. But, knowing this, players will be tempted to behave poorly in the round before and so forth. Thus, if players were good game theorists, we should expect to observe no transfers from the outset. The experimental results do not confirm this simple theoretical result. Indeed the dynamics of the offers and return transfers turn out to be quite subtle.

Several recent experiments have investigated the neural correlates of the trust game via different methodologies. In a first study [91], the activity of the brain of the two players was recorded using a method known as *hyperscan functional magnetic resonance imaging* (h-fMRI; [114]). One of the main results addresses the temporal dynamics of the decision. The moment at which the trustee activated a certain network of brain activity (anterior cingulate cortex and caudate nucleus) was correlated with a decision regarding how much money to return. During the first rounds this network was activated *after* the offer was made by the investor but, in later rounds, the activity peaked *before* the investor's offer was revealed. According to the authors, the trustee built a reputation for the investor, i.e., someone he could trust or not, and switched from a *reactive* to an *anticipatory* strategy. [91][6] This study opens a perspective that goes beyond the sole localization of cerebral activity generally reported in functional MRI studies. It provides important information on the *dynamics* of the trustee's decision by showing a time difference in cerebral network recruitment of the order of 14 s between early and late rounds of the game.

A related study investigated the players in the trust game after asking them to breathe puffs of oxytocin delivered by a spray [103]. Oxytocin is a neuropeptide known, among other things, to enhance social links, to play an active role in childbirth and, maybe more surprisingly, to make people more generous and trustful [61], [133], [173], [174], [177]. Briefly, Kosfeld *et al.* [103] found that investors who had sniffed oxytocin tended to entrust more money compared to a control group that received a placebo. Subsequent control experiments showed that oxytocin affected "social trust" but not the propensity of the investor to take risks *per se*. For instance, oxytocin had a significant effect on the investor's decisions only when he interacted with a human being but not with a computer. Also of interest was that breathing oxytocin had no significant effect on the behavior of the trustees.

The foregoing studies [91], [103], tackle the issue of trust-related decisions in very original ways thanks to different methodologies (neuroimaging and neuroendocrinology). Let us examine some of the logical (although very simplistic) assumptions people who are not neuroscientists might make after reading these results. In the experiment in which h-fMRI was employed [91], an additional result reveals that the investor's medial cingulate gyrus was significantly more active when deciding the amount of money to share with the trustee. Given that oxytocin tends to make the investor offer more money, one might then expect to find receptors of oxytocin on the cingulate gyrus. However, to our knowledge, there is no result which confirms this expectation. It is known that oxytocin modulates the activity of the amygdala [107], a central component of the neuro-circuitry of fear and social cognition that has been linked to trust and which does contain a significant number of oxytocin receptors [69]. Kirsch *et al.* [98] show that the functional connectivity of the amygdala with midbrain regions known to participate to social cognition and fear is modified after breathing oxytocin. However, the study by King-Casas *et al.* [91] does not mention a role for the amygdala in decision making during the trust game. This does not, by any

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[6] Other experiments also report an important role of the caudate nucleus in the decision to invest in the trust game in different contexts. For instance, de Quervain *et al.* [28] found a modulation of this brain area when the possibility existed to punish the other player if trust were breached. In a related experiment, Delgado *et al.* [31] used fMRI to investigate the role of the perception of moral character of the trustee on the investor's behavior and shed new light on the neural correlates of the learning processes at stake during the trust game.

means, say that the amygdala was not involved in the investor's decision-making process. What the results might suggest is simply that any metabolic changes in investors' amygdala activity during the rounds did not reach significance compared to the medial cingulate gyrus. It is noteworthy however, that several studies report an important role of the amygdala-hippocampus-cingulate gyrus connections in primate pair bonding [5] and in optimism bias in humans [142], therefore hinting at how oxytocin may affect investors' decision making.

Despite the insights yielded by these studies on decision making in the trust game, answers to questions regarding how to link cerebral blood flow and neuroendocrine probes of cortical function were still pending until a more recent study. Baumgartner *et al.* [7] used fMRI to estimate brain activity of the investor in the trust game under oxytocin or not. Hence, this study uses both methodologies: neuroimaging [31], [91] and neuroendocrinology [103], [173]. In their design, the authors compared a placebo and an oxytocin group of investors in situations where trust was violated in 50% of the cases providing them with information about those cases in which a breach occurred and those in which it did not. At the behavioral level, investors in the placebo group shared less in the trust game after finding out their trust had been (or could be) breached compared to their behavior before knowing [7]. Conversely, the oxytocin group maintained their decisions to share money regardless of breaches of trust. Interesting neural differences accompanied behavioral observations. The amygdala and caudate nuclei of participants under oxytocin showed significantly lower activity compared to those who sniffed a placebo. As expected in light of previous findings [103], the differences between placebo and oxytocin groups at two different levels of description (behavioral and brain) were not found when investors played the risk game against a computer [7]. Hence those results strengthen previous hypotheses and results favoring a role of oxytocin in minimizing fear, facilitating pro-social decisions and trust, at least in the context of this particular trust game [173].

Consider now the example of the *ultimatum game* (UG) in which a first player, the *proposer*, offers a share of a certain amount of money to another player, the *responder* [57]. If the responder accepts the proposer's offer, both players keep their respective share of the money. However, the responder can simply refuse the proposer's offer. In this case neither receives any money. If both the proposer and the responder make decisions in a rational homo œconomicus fashion and therefore behave as *rational maximizers*, the proposer would offer the minimum amount and the responder would accept it, even a penny being better than nothing (at least in theory).[7] However, this raises an important question. If individuals' utility depends not only on their own payoff but also on the payoff of the other then it is possible to explain peoples' behavior as corresponding to the maximization of a utility function. In particular such a utility function might rank "unfair" offers below situations in which neither player gets anything [39]. Indeed, in general, if the division proposed gives less than a third of the sum to the responder, it is highly likely that the responder will refuse it. One standard interpretation of this behavior is that the responder is punishing the proposer for being unfair.[8] This is somewhat different from saying that people are averse to unfair splits and suggests some reaction to the specific actions of the partner. In any event, the rejection of "unfair" splits has been consistently reported (with slight modulations) in many countries with diverse levels of economic development [17], [65]. For example the same phenomenon was observed in Indonesia even when three times the monthly expenditure of participants was at stake [20]. This finding runs counter to the argument that people only reject unfair shares when small sums are to be earned (or lost) whereas they are more "rational" when the sums involved are large.

Using functional MRI, Sanfey *et al.* [137] recorded the responder's brain activity during a one-shot UG (i.e., with no repeated rounds). They showed that unfair offers, when processed, involved significantly higher activity in parts of the brain involved in emotion (e.g., insula), cognition (dorsolateral prefrontal cortex, DLPFC) and resolving cognitive conflict (cingulate cortex). The authors also reported that activity in the insula, compared to the DLPFC, can help predict whether an unfair offer may be rejected or not.

Using a technique called *repetitive Transcranial Magnetic Stimulation* (rTMS; [11], [35], [126]) that allows to temporarily inhibit the functioning of cortical brain regions, another research team altered the decisions of the responder in the UG [100]. By delivering rTMS trains to the right DLPFC (BA 46; the precise coordinates being those found in the previous experiment [137]) of the responder, they managed to induce him to accept more unfair offers than players that had not received the rTMS pulses. One of the most intriguing features of this result lies in the fact that inhibition of the DLPFC (and perhaps nearby regions?) by rTMS alters decisions. Interestingly, the authors also report that it did not alter the responder's judgments regarding the fairness of the offer. This might be an even stronger result: rTMS delivered on the right DLPFC induced the responder to accept more offers even though he was fully aware that, from his point of view, they were unfair. It is noteworthy, however, that another study using TMS on DLPFC during the UG did not reach such a clear-cut result [163].

Finally, two UG studies revealed that responders who suffer from brain damage in prefrontal regions of the brain (ventromedial prefrontal cortex, VMPFC) tend to make more emotional decisions compared to subjects with unimpaired brains. Koenigs and Tranel [102] found that, when playing the responder's role in the UG, VMPFC patients had a higher rejection rate of unfair offers compared to responders with healthy brains. Moretti *et al.* [115] also report this finding on VMPFC patients albeit with a minor nuance. The rejection rate was higher only when the financial gain was to be received later. If gains were available immediately, there were no significant differences between the VMPFC and unimpaired (control) groups on decisions whether to accept or refuse offers.

Over and above contributing to a better understanding of the cerebral underpinnings of decision making during the UG, these

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[7] A recent experiment where chimpanzees played an adapted version of the ultimatum game revealed they behaved like rational maximizers and accepted what humans would consider unfair offers [73].

[8] A study recently published by Zak *et al.* [174] showed that, in the ultimatum game, if the proposer sniffs puffs of oxytocin he tends to make an offer to the responder that is superior to the offers made by participants who sniffed a placebo.

studies suggest at least three important issues regarding the interactions between levels of analysis.

First, if one takes the rTMS study by Knoch *et al.* [100] in an isolated way, i.e., without knowing the fMRI results published by Sanfey *et al.* [137], one might be tempted to assume that the DLPFC plays the main part in decision making since its disruption leads to a switch in decision. However, Sanfey *et al.* [137] showed that when a decision is made, at least the cingulate cortex and the insula are also engaged and that it is the change of activity in the insula that predicts the responder's decision. Thus, the decision as to whether an unfair share should be accepted or not stretches far beyond some localizational hypothesis about how the brain works. The same applies to studies that show how changing a single parameter (the immediacy of the reward) modulates decisions in VMPFC studies [115].

A second point is that two studies [100], [163], using the same technique to alter the functioning of the same brain area (the right DLPFC of the responder) in the UG appear to provide contradictory results. Knoch *et al.* [100] managed to significantly alter the responders' decisions whereas the main result in van't Wout *et al.* [163] work was an increase in decision time with no modification of the decision.

Finally, dysfunction of different parts of the prefrontal cortex whether with rTMS (DLPFC, Brodmann's area 46; [100]) or because of brain damage (VMPFC, Brodmann's area 10, 11, and 25; [102]) led to opposite results: the former favoring acceptance of unfair offers and the latter more rejections.

These studies using methods as diverse as functional MRI, simulated (rTMS) or real brain damage, confirm that the prefrontal cortex plays a major role in decisions regarding unfair offers in the UG and, to some extent, in social decision making [135]. In the context of the UG game, emotions are thought to bias decision towards rejecting unfair offers whereas cognition (DLPFC) would favor acceptance. However, disruption of the DLPFC clearly leads to a reduction in emotional reactions [100], suggesting that this area may play a strong role in up-regulating emotions [118]. Hence, beyond social neuroeconomics itself, studies on the neural underpinning of the UG shake the mainstream and simplistic picture referring to the dorsolateral prefrontal cortex as a part of the brain only in charge of "rational thinking." They motivate a rethinking of the classical dual systems model (emotion versus cognition) used in neuroscience to explain decisions in social contexts [153], [154]).

All the findings on the neural underpinning of decision making in the ultimatum game can be considered as laying the foundations of a better understanding of social neuroeconomics. However, none of these studies raises the question of how information is exchanged in social decision making, for example, within the prefrontal cortex itself (e.g., DLPFC and VMPC) as well as with other areas of the brain.[9]

The question of information exchange and its modulation under different rapidly changing contexts is of growing importance in (social) neuroeconomics especially since a substantial load of data is accumulating without necessarily connections between the levels of description at which the studies have been conducted. In experimental and behavioral economics, studies have investigated the effects of a myriad of socio-cultural parameters on decisions in games such as the UG [17]. Today, the role of more "socio-biological" factors occurring at various levels of description such as oxytocin [174], serotonin [27], [37], addiction to smoking [152], the level of testosterone [16] and even heritability [168], gene expression [99], and schizophrenia [1] is found to modulate decision in the UG.

The examples of the investigation of the neural underpinning of decision in the trust and the ultimatum games make it clear that a coherent framework for both the integration of data collected at various levels of analysis and also for analyzing the dynamics of decision making itself is 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.

## V. SHARED COORDINATION DYNAMICS OF BRAIN AND BEHAVIOR

Motivated by early [79], [81], [83], [164] and more recent [41], [160] converging hypotheses on the role of *neural synchrony* in the emergence of cognition, we propose to discuss some of the issues presented in Section III in the context of self-organizing dynamical systems.

Why do we think there could be a "unified" theoretical framework to understand the neuroscience of decision making at behavioral and brain levels?

A number of basic coordination phenomena exist that seem to cut across a wide range of levels, creatures and functions. Coordination phenomena appear 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 [88] describe the following: 1) patterned states of coordination remain stable over time despite perturbations, 2) component parts and processes are (dis)engaged in a flexible fashion depending on functional demands and/or environmental conditions, 3) the existence of multiple coordination states, i.e., *multifunctionality*, 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 [81]. *Why should economic decision making be an exception?*

Neuroeconomics, from this point of view could be conceived 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(s). 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 ([14], [15], [34], [46], [81], [141], however, see [123], [129], and [130] for recent suggestions in that direction).

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[9] Some light is shed by a study published by Longe *et al.* [110] reporting a "dynamic interplay" between lateral prefrontal cortex and VMPFC, the latter hypothesized to play an "emotional gating" role when tasks are accompanied by a high cognitive demand.

Hayek's quote at the beginning of this article could be misleading regarding how economists consider comparisons to a termite colony or to a beehive that are among the social systems generally presented as governed by the principles of nonlinear dynamics and self organization [104], [105]. Although those organizations are in some sense "optimal," most economists would doubt that this optimality is achieved in the same way as it is in an economy or market and this perspective is too often referred to as "unorthodox economics" [96]. At the same time, there is now a wide consensus regarding the self-organized nature of the brain (and interactions of multiple brains), where phase synchrony emerges when information is exchanged on various scales from neurons to individuals [34], [81]. In addition, recent advances in the brain and movement sciences have revealed the self organized and informational nature of human behavior and cognition [14], [77], [78], [80].

In the neuroeconomics field, a novel way to look at the issue of nonequivalence between levels of analysis would be through the lens of coordination dynamics, and the synchronization that emerges at different levels in the brain [81], [128], [151], [164], between the brain and the environment [90] or between two bodies/brains [120], [121], [156], [157]. 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 behavior and the dynamics of the brain [82], connecting these levels by virtue of their shared dynamical properties [50], [86], [87]. The high temporal resolution of electroencephalography (EEG) and magnetoencephalography (MEG) was exploited to quantify the relationship between behavioral 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 behavioral dynamics revealed in experiments on coordination dynamics [81]. 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 behavior. Of particular initial interest was the identification of qualitative changes in the pattern of neural activity that occurred simultaneously with transitions between behavioral coordination patterns. More precisely, a phase transition from one behavioral pattern to another was accompanied by a similar phenomenon at the brain level suggesting that both are governed by the same coordination dynamics [50], [86], [87]. Indeed, in a number of circumstances it has proven possible to derive the behavioral dynamics from a biologically plausible model of the brain dynamics called the *neural field* [48], [74], [75], [89]. The foregoing findings paved the way for more recent work in the domain of social interactions that may provide new perspectives in social neuroeconomics [38], [135].

Kelso *et al.* developed a research program involving behavioral and neural investigation of social coordination dynamics that, for the first time, allowed for a real-time quantification of the level of bonding between people during and after social encounters together with their neural underpinning [120], [121], [156], [157], (see [124] for a review). Using the coordination dynamics framework, they shed new light on how social processes are integrated in the brain using a specially designed dual-electroencephalogram system (dual-EEG) to identify neural signatures, referred to as *neuromarkers* of social coordination, that (dis)appeared with emergence/dissolution of coordinated behavior [156] and hinted at how the intention to coordinate in social settings is represented at the cortical level [157]. Hence, *social coordination dynamics* allowed to identify new neural mechanisms underlying social interactions that (dis)appeared at the same time as their behavioral correlates. Such concomitant effects occurring in the brain and between individuals offer another illustration of the shared dynamics between levels and how coordination dynamics may help to bridge the gaps between levels of analysis [124].

The experiments described [50], [86], [87], [156] support the potential for considering decision making dynamics at the behavioral and neurophysiological levels in a common dynamical systems perspective. In addition, experiments on the coordination dynamics of learning revealed that the acquisition of new behavioral patterns is accompanied by specific neuromagnetic activity in alpha and beta bands reflecting learning-induced increases in coordinative stability [71].

Hence, strong hints exist that the theoretical cum empirical framework of coordination dynamics could serve as an interesting entry point to address the issue of nonequivalence between levels of analysis in neuroeconomics. 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 one decision or another. A good example could be the responder's decision to accept or not offers made by the proposer in the ultimatum game (see Section III). One could consider each decision (accept or refuse) as an *attractor* in the *phase space* that could evolve depending on the nature of the offer and the context. In classical economic theory, regardless the offer (unless it is 0), the homo œconomicus responder should always have two options: accept or refuse and chooses to accept. Experimental results do not verify this assumption. For certain values of the offer, only one decision is made and the responder's decision will evolve with the offer. For instance for low offers the responder refuses and at a certain ratio (generally above 7:3 according to the literature [17]), he might switch from refusing to accepting the offer (*vice versa* depending on the initial conditions). In Fig. 2, the dynamics of the responder's decision in the UG is represented by the overdamped movement of a particle (filled circle) in the landscape of a *potential function*.[10]

Minima in the potential landscape represent the alternative that the responder is offered as a function of the offer he has to process. The offer is a *control parameter* that is going to constrain the system and force the potential to change. The control parameter is a non specific independent variable that moves the system through different states without prescribing them [81]. For example, when the ratio is 9:1 in favor of the proposer, only one attractor exists in the phase space (Fig. 2). Hence, the only alternative for the responder is to refuse. As the amount of money proposed to the responder increases [Fig. 2(A), left

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[10] Fuchs and Kelso [49] elegantly described the overdamped movement of the particle as a movement in a very viscous fluid such as honey, where the particle does not oscillate around a minimum but gets stuck.

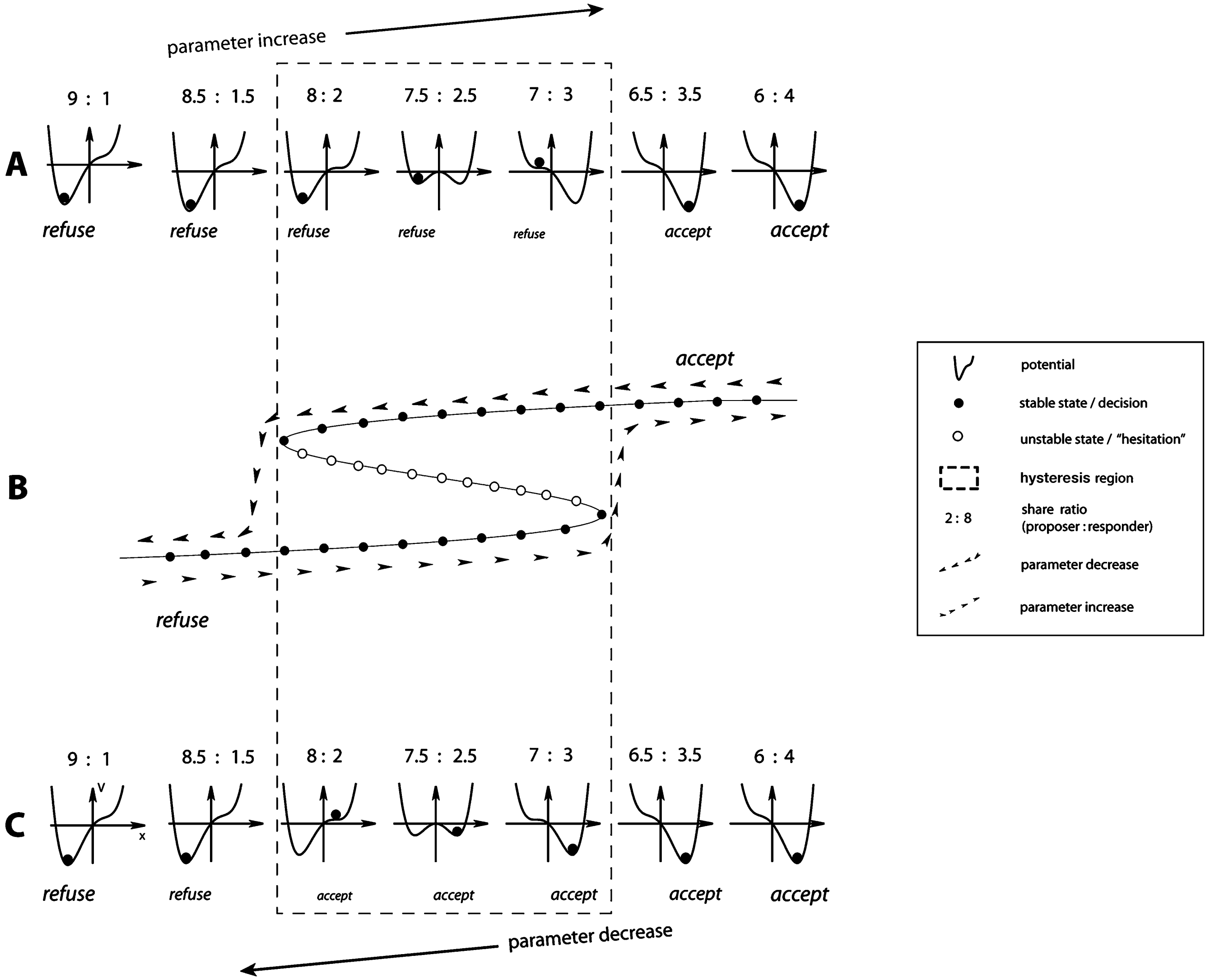

Fig. 2. Phase transition between decisions of the responder in the UG. In this figure we model decisions made by the responder with respect to offers by the proposer in the UG. Changes in potential landscapes of the responder's decision are represented as the amount of money offered by the proposer. The switch from refusing to accepting (A) and from accepting to refusing (C) are asymmetrical: in the so-called *hysteresis region*, the responder can either accept or refuse the same amount depending on initial conditions or previous context. (B) White particles represent unstable states whereas black ones represent stable states. See text for details (adapted from [88]).

to right] the potential evolves and a second alternative appears gradually. The minimum of the "refusal" attractor gets shallower until it becomes a *repeller*. A new attractor has emerged: acceptance. At a critical value of the ratio, the responder switches from refusing to accepting: a phase transition occurs. If one changes the offer ratio in the other direction [i.e., moving from an offer that favours the responder towards an offer that favours the proposer; Fig. 2(C), right to left], the "acceptance" attractor will gradually disappear and the "refusal" one will emerge. For extreme values of the ratio, the decision is quite stable as the attractor is deep. For these offers, if one perturbs the particle it relaxes very rapidly to its equilibrium position. This phenomenon is known as *critical slowing down* [139]. Of particular interest is that the (hypothesized) phase transitions from accepting to refusing or from refusing to accepting do not occur at the same value of the offer (the control parameter).

A *hysteresis region* can be observed in the potential where both attractors co-exist and therefore both decisions (acceptance or refusal) can be made for the same value of the offer. In this region located in the vicinity of the phase transition, the behavior is not stable (Fig. 2(B), white particles). Many factors can determine what decision is made within this region including a high sensitivity to initial conditions. This is known as the *hysteresis* effect. This kind of modelling is unusual in the context of studies in neuroeconomics but has received a wide coverage in the domains of cognitive psychology and neurobiology [81], [149], [159]. As mentioned earlier, of particular interest is that shared dynamics allows to observe phase transitions at different levels of description [50], [86], [87], [156] and that neural indices of behavioral instability (be it motor or cognitive in nature) are common across a wide set of experimental settings (see [122] for a review). Because fluctuations play such a significant role in the coordination dynamics framework, Schöner, Haken, and Kelso [140] used the Fokker–Planck equation as a means of describing the selection among alternative behavioral patterns as a stochastic process (see also [143]).

In the neuroscience of decision making, a very interesting approach in this direction can be found in Roxin and Ledberg [132] 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 behavioral and neurophysiological dynamic decision making, modelled as a pitchfork bifurcation [150]. Roxin and Ledberg's work should thus be of great interest for the neuroeconomics community (see also [146]). The same is also true of advances in the *neurodynamics* field where the work by Deco *et al.* [109] stresses the key role of attractor dynamics in a network of interconnected neurons involved in generating a cognitive process. They argue in favor of considering 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 (see also [175] and [176] in the context of human skill learning). Along similar lines, Loh *et al.* [108] explored the dynamics of the prefrontal cortex in cognitive tasks in which stimuli had to be associated with actions by trial-and-error learning. They 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, these results could be of great interest in disentangling the intrinsic dynamics of the prefrontal cortex in the ultimatum game.[11]

## VI. LARGE–SCALE CORTICAL DYNAMICS AND METASTABILITY

Local dynamics are not the only relevant thing here, since synchronous neural oscillations have been identified in specific parts of the brain [143] as well as at larger scales, i.e., between distant cortical structures [6], [81], [164], [166]. 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* [47]. Various studies have revealed the existence of residual variable fluctuations in cerebral activity that appears to be synchronized in different brain locations [45]. These fluctuations are low frequency oscillations that are an intrinsic property of the (a)symmetrical cortices and have been found in various areas of the brain [12]. Such fluctuations corroborate the existence of functional connectivity, i.e., a descriptive measurement of the correlations between distinct areas of the cerebral cortex [47]. 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 analyses. Indeed, this method not only makes it possible to identify the brain areas that are functionally (inter)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 areas involved in cognition and emotion (if this dichotomy still stands).

Among the many ways that can be used to compute fMRI [98] and EEG functional connectivity [43], one is of particular interest in our theoretical framework as it is based on *self-organizing map* algorithms (SOM; [127]). This technique makes it possible to compare areas pairwise without having to use a function of reference or to define specific areas of interest. For example, if one takes the results of the fMRI version of the ultimatum game [137], a functional connectivity analysis might help provide more accurate information regarding the exchanges between the DLPFC, the anterior cingulate and the insula such as what the temporal sequence of these interactions is. Furthermore, it is possible to analyze functional connectivity prior to, during, and after, a given task. At first, one could obtain information regarding intrinsic connectivity only when the subject was at rest (decision wise), i.e., independent of the particular task. It will be interesting to see whether making the decision allows this synchronization of oscillations at low frequencies or if this information exchange existed already in the absence of the decision task. If the latter were the case, it may be that connectivity is more structural than functional. If connectivity does not exist in the period of initial rest and if it emerges when the decision is to be made, it is then interesting to know if it persists in the rest phase that follows the task. In this case, connectivity would be determined by the context of the task. Consequently, connectivity would be sensitive to the history of the system, and therefore be highly context-dependent [106].

Context-dependent synchronization of oscillatory neuronal responses has been observed within and between various areas of the brain illustrating how it can function in an integrated fashion. A novel aspect of coordination dynamics is that where stable states of coordination do not occur, a more subtle metastable *regime* exists [34], [46], [81]. Metastability has been hailed as a "*a new principle of brain function*" [40]. In coordination dynamics, 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*; [81]). Notice again that the latter alone is often proposed as a solution to the binding problem [54], [131], [145]. But in metastable coordination dynamics, the two polar tendencies of specialized brain regions expressing their autonomy and working 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 behavioral and brain networks [13], [33], [42], [46], [81], [158]. In the words of Varela *et al.* [164]: *"The emergence of a unified cognitive moment relies on the coordination of scattered mosaics of functionally specialized brain regions* $[\cdots]$ *mechanisms of large-scale integration*

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[11] We explained earlier that inhibition or dysfunction of different parts of the prefrontal cortex led to opposite economic decisions [100], [102], [115].

*that counterbalance the distributed anatomical and functional organization of brain activity enable the emergence of coherent behaviour and cognition. Although the mechanisms involved in large-scale integration are still largely unknown, we argue that the most plausible candidate is the formation of dynamic links mediated by synchrony over multiple frequency bands."* Metastable coordination dynamics takes this a step further by offering a means for the *creation* of information: choice and decision making is the process of transiting from metastability to stability and *vice-versa* [83]. To be clear, moving from a metastable tendency (no fixed point) to a stable state (fixed point) reflects a fundamental decision.

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 [169].

## VII. Conclusion and Directions for Future Research

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 [136]. 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 [136]. This principal multiagent view might be right but tells us little or nothing about how levels are linked and how information is exchanged within and between them.

An alternative approach to this purely hierarchical model is coordination dynamics [81]. 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 behavioral 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. Patterns of coordinated behavior and pattern dynamics (multistability, critical fluctuations accompanied by a temporary loss of stability, phase transitions, hysteresis and critical slowing down) have been observed within an individual, between an individual and the environment and between individuals. In this respect *social coordination dynamics* [120], [124] complements recent developments in social cognitive neuroscience, behavioral economics, game theory, socio-economics and neuroeconomics. Hence, as a conceptual framework for spontaneous decision making that respects the dynamics of both the brain and the economy, coordination dynamics could become a central concept in the development of the transdisciplinary field of neuroeconomics [88], [123].

Up to this point the emphasis was still on the individual's decision process and his emotional or reasoned reactions to the situations he was confronted with. To move on to social neuroeconomics requires accepting the idea that individuals are continually taking account of and reacting to the behavior of others. However, the analysis has essentially been confined to situations in which the individuals are not influenced by the physical presence of their partners or competitors. The interaction remains at an abstract level. Yet what we are supposed to be modelling is real life situations with strategic interaction and possible conflicts of interest. These, in reality, often involve direct interaction with others who are physically present. As Ludwig von Mises [165] put it: *"Economics deals with the real actions of real men. Its theorems refer neither to ideal nor to perfect men, neither to the phantom of a fabulous economic man (homo œconomicus) nor to the statistical notion of an average man (homme moyen)."* Thus, interactions should be considered not only as a mental process but also as one involving physical signals and not only through intangible information in the economic sense. Yet, to date, one particular feature of (social) neuroeconomics is that decision making processes are always studied in a body- and movement-independent fashion—at least in most of the scientific literature dedicated to the neuroscience of decision making (but see [10]). Why is this? One reason might be conceptual in origin: in behavioral and brain sciences, historically, the mind $\sim$ body dichotomy established a tenacious conceptual hierarchy between so-called "high level" cognitive functions and "low level" motor mechanisms. Hence, the body and motor component have long remained a less interesting component of decision making processes. However, this tendency has been challenged in the past decade thanks to the advent of what is known as *motor cognition* [72].

Social coordination dynamics and its dynamical measures have proven an adequate means of analyzing quantitatively the spontaneous coupling between individuals, the transition to loss of entrainment and the effect of the social encounter at both behavioral and brain levels during and after the interaction (see [124] for a review). For instance, a finding such as the neuromarkers of intentional and non intentional social coordination could turn to be crucial to a better understanding of the competition $\sim$ cooperation mechanisms underlying decisions in economic contexts such as public coordination games.

In sum, (social) coordination dynamics provides conceptual framework that encompasses the dynamics of both neural and behavioral levels. This is very different from the usual economic analysis which focuses on one level, and is not concerned with way in which the dynamics of the coordination of the activities and decisions of the interacting individuals at one level yields different phenomena at a different level. However, taking explicit account of the coordination dynamics, may provide a route towards bridging the gaps between different levels of analysis and thus clear a path for new multilevel, interdisciplinary investigations of social interactions including those occurring in the context of economic transactions.

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