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THE NEUROECONOMICS OF DEPTH OF STRATEGIC REASONING*

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Bounded rational behaviour is commonly observed in experimental games and in real life situations. Neuroeconomics can help to understand the mental processing underlying bounded rationality and out-of-equilibrium behaviour. Here we report results from a recent study on the neural basis of limited steps of reasoning in a competitive setting – the beauty contest game. We describe how a cognitive hierarchy model fits both behavioural and brain data.

1. INTRODUCTION

ECONOMISTS only recently departed from the rational man and the notion of common knowledge of rationality when theorizing on economic problems. Common knowledge of rationality means that a decision maker knows that he is rational, that he knows that the other decision makers are rational and that he knows that others also know that everybody is rational, and so on. A rational agent maximizes his expected utility, which means that a utility of different results are weighted by their objective or subjective probabilities and maximized. Experimental economists have provided in the last two decades experimental results showing how far humans comply with or deviate from these assumptions, thus corroborating theories of bounded rationality.

Here we use a neuroeconomics approach, combining economics and neuroscience, to study bounded rational behaviour determined by limited depth of reasoning on players' beliefs about one another in a competitive interactive setting – the beauty contest game. The game was inspired by a quote from the *General Theory*:

Professional investment may be likened to those newspaper competitions [the beauty contest] in which the competitors have to pick out the six prettiest faces from a

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hundred photographs, the prize being awarded to the competitor whose choice most nearly corresponds to the average preferences of the competitors as a whole; so that each competitor has to pick, not those faces which he himself finds prettiest, but those which he thinks likeliest to catch the fancy of the other competitors, all of whom are looking at the problem from the same point of view. It is not a case of choosing those which, to the best of one's judgment, are really the prettiest, nor even those which average opinion genuinely thinks the prettiest. We have reached the third degree where we devote our intelligences to anticipating what average opinion expects the average opinion to be. And there are some, I believe, who practice the fourth, fifth and higher degrees.

(Keynes 1936)

Keynes describes different ways of thinking about others in a competitive environment. This can range from low levels reasoning, characterized by self referential thinking (choosing what you like without considering others' behaviour), to higher levels of reasoning, taking into account the thinking of others about others («third degree»), and so on.

Many features of social and competitive interaction require this kind of reasoning; for example, deciding when to queue for precious theatre tickets or when to sell or buy in the stock market, before too many others do it.

Why do people use different and limited numbers of steps of reasoning? As the number of steps of thinking increases, the decision rule requires more computation; and higher level of reasoning indicates more strategic behaviour paired with the belief that the other players are also more strategic (Camerer *et alii* 2004). One reason for the limited steps of reasoning is that players might be incapable in using high level of reasoning due to cognitive limitations; or another reason is that a player might believe (overconfidently) (Camerer and Lovallo 1999) that others will not use as many steps of thinking as he does.

Identifying the neural correlates of different levels of reasoning, and more specifically, being able to distinguish between low – *versus* high – level reasoning people according to their brain activity will help to explain the heterogeneity observed in human strategic behaviour.

2. THE EXPERIMENTAL BEAUTY CONTEST GAME

Nagel (1995) studies an experimental competitive game, analogous to the Keynes's Beauty Contest, to characterise different levels of strategic reasoning. In the experimental game, participants choose a number between 0 and 100. The winner is the person whose number is closest to $2/3$ times the average of all chosen numbers. This game is suitable for investigating whether and how a player's mental process incorporates the behaviour of the other players in his strategic reasoning. Game theory suggests a process of iterated elimination of weakly dominated

strategies which in infinite steps reaches the unique Nash-equilibrium in which everybody chooses 0.

However, «the natural way of looking at game situations is not based on circular concepts [as for the Nash equilibrium] but rather on a step by step reasoning procedure» (Selten 1998, 421) which typically results in out-of-equilibrium behaviour.

2. 1. The cognitive hierarchy model

This step reasoning can be some finite steps of the iterated elimination process or of the so-called iterated best reply, a Cognitive Hierarchy of thinking, that better describes behaviour in the beauty contest game (Nagel 1995, Stahl and Wilson 1995, Camerer *et alii* 2004). For instance, a naïve player (level 0) chooses randomly. A level 1 player thinks of others as level 0 reasoning and chooses $33 (= 2/3 * 50)$, where 50 is the average of randomly chosen numbers from 0 to 100. A more sophisticated player (level 2) supposes that everybody thinks like a level 1 player and therefore he chooses $22 (= (2/3)^2 * 50)$. And, as Keynes mentioned there might eventually be people reaching the (Nash) equilibrium of the game, and thereby choosing 0. According to the Cognitive Hierarchy model a subject is strategic of degree k if he chooses the number $50 M^k$, called iteration step k . Choices in many beauty contest experimental games (Nagel 1995, Ho *et alii* 1998, Bosch-Domenech *et alii* 2002, Costa-Gomes and Crawford 2006) show limited steps of reasoning, a bounded rational behaviour, confirming the relevance of the iterated best-reply model. Behavioural experiments of this game have been widely studied (see, e.g. for lab experiments Nagel 1995; Ho, Camerer, Weigelt 1998; Costa-Gomes, Crawford 2006 or as newspaper competitions announcing the rules of the game and inviting readers of *Financial Times*, *Die Zeit*, and others to participate, see Bosch *et alii* 2002). These studies successfully identify high vs. low level of reasoning according to the chosen numbers spikes at or near 33 (level 1), 22 (level 2), and 0 (infinite level = equilibrium), the theoretical numbers according to the above discussed process.

3. AN fMRI STUDY ON DEPTH OF REASONING

In Coricelli and Nagel (Coricelli and Nagel 2009) we used functional magnetic resonance imaging (fMRI) to measure brain activity when subjects participated in the beauty contest game. We introduced two main conditions in an event-related fashion. In the *human condition*, each participant of a group of 10 was asked to choose an integer between 0 and 100. The winner is the person whose number is closest to the target number (a parameter multiplier (e.g., $2/3$) times the average of 10 num-

bers). In the *computer condition* one participant chose one number and a computer algorithm chose randomly (and independently of the multiplier parameter) nine numbers. The prize for the winner was 10 euros in each trial of both conditions, or a split of the prize in case of ties. The computer condition should invoke low levels of reasoning (at or near level 1) according to the iterative reply model. In contrast, in the human condition a higher variety of levels of reasoning should be observed since players might have different ideas what other players choose. To be able to identify brain activity related to mental calculation most likely involved when deciding in the game, we introduced calculation tasks in which subjects were asked to multiply a given parameter (called C₁ condition) or the square of a parameter (called C₂ condition) with a given integer.

*3.1. Bounded rational behaviour:
participants played according to the cognitive hierarchy model*

As found in previous experimental economics studies of the game (Nagel 1995, Stahl and Wilson 1995, Bosch-Domenech *et alii* 2002; Camerer *et alii* 2004), in Coricelli and Nagel (Coricelli and Nagel 2009) the behavioural results confirmed the presence of play according to the iterated best reply model. The starting point for the reasoning process was 50 and not 100, and the process was driven by iterative best replies and not by elimination of dominated strategies. We measured the level of reasoning of a subject as the smallest quadratic distance between actual play and the different theoretical values based on the Cognitive Hierarchy model. We categorized each player according to three categories: random behaviour, low level (level 1), and high level of strategic reasoning (level 2 or higher). The high-level reasoning subjects clearly differentiated their behaviour in the human compared to the computer condition. They behaved as level 1 in the computer condition but were classified as higher level of reasoning (level 2 or more) when interacting with human counterparts. The subjects classified as low level behaved similarly against the computer or the humans: at or close to level 1 in both conditions. Few subjects behaved in a quite random fashion.

3.2. Neural correlates of depth of reasoning

In Coricelli and Nagel (2009) we found enhanced brain activity in the medial prefrontal cortex (mpfc), ventral anterior cingulate (acc), superior temporal sulcus (sts) and bilateral temporo-parietal junction (tpj) when subjects made choices facing human opponents rather than a computer. The foci of activity in the mpfc (peak MNI coordinates, x = 0, y = 48, z = 24) is consistent with results of many studies on theory of

mind or mentalizing (Fletcher *et alii* 1995, Gallagher *et alii* 2000, McCabe *et alii* 2001, Bird *et alii* 2004, Amodio and Frith 2006). Psychologists and philosophers define theory of mind or mentalizing, as the ability to think about others' thoughts and mental states in order to predict their intentions and actions.

When we analyzed separately high- and the low-level reasoning subjects, we found the activity in the medial prefrontal cortex to be stronger in subjects classified as high level. In the high reasoners, guessing a number in the human condition activated two main regions of the medial prefrontal cortex, a more dorsal and a more ventral portion of the anterior MPFC.

High levels of reasoning in the guessing game implies thinking about how other players think about the others' (including yourself) thinking or behaviour, and so on. In other words, high reasoners might assume that the same reasoning they are performing, – namely best replying to random players – is likely performed by others, thus inducing a process of iterative thinking.

The prefrontal activity of the low-level reasoning subjects was found in the ventral anterior cingulate cortex, an area often attributed to self referential thinking in social cognitive tasks (Moran *et alii* 2006). Thinking about the others as random players, thus considering them as 'zero-intelligent' agents, requires only a first person perspective of the interactive context.

fMRI results show additional brain activities related to high- versus low-level reasoning in the right and left lateral orbitofrontal cortex and left and right dorsolateral prefrontal cortex, areas likely related to performance monitoring and cognitive control (Koechlin and Summerfield 2007). This suggests that a complex cognitive process subserves the higher level of reasoning about others.

The guessing game also requires solving a complex calculation task. Thus, in order to follow a first or higher level of reasoning, the subjects need to think what might be the average of the numbers guessed by the others, including into this average their own number, and then multiplying the result by the announced factor, one or more times. Bilateral activity in the parietal cortex, encompassing the angular gyrus, the inferior parietal lobule, and the supramarginal gyrus, was found both in the human and computer conditions. Results from our calculation task show enhanced activity in the angular gyrus and in the inferior parietal lobule when the subjects were requested to mentally multiply a factor times a number (C1 condition), and greater activity in the same areas when they were asked to multiply twice the same factor times a number (C2 condition). Suggesting that part of the calculation activity related to the beauty contest game might be performed by these portions

of the parietal cortex. Additional activity related to calculation (both C1 and C2 conditions) was found in the lateral prefrontal cortex. Notably, no activity of the medial prefrontal cortex was related with any kind of calculation.

In Coricelli and Nagel (2009) we found a cross-subject correlation between a measure of strategic IQ in the beauty contest (computed as the distance of own choice to the target number, M^* average of all chosen numbers, across all trials) and brain activity in the mpFC. Strategic IQ is reflected by the ability of subjects to match the right guess using higher levels of reasoning, that is, the ability to think deeply about others. Strategic IQ was not correlated with accuracy (number of exact responses) in the calculation task, thus it is independent of cognitive or calculation skills. Notably, no other brain region of interest was correlated with strategic IQ. This suggests that the mpFC, involved in higher reasoning about others, leads to successful outcomes in our interactive setting.

4. HOW NEUROSCIENCE CAN INFORM ECONOMICS: SPECIFICATIONS OF THE UNDERLYING PROCESSING OF HUMAN'S OUT-OF-EQUILIBRIUM BEHAVIOUR

The guessing game is suitable for investigating whether and how a player's mental process incorporates the thinking process of the other players in strategic reasoning. We provide a computational account of the cognitive processing underlying actual choices in the experimental game, in order to identify the neural substrates of different levels of strategic thinking. The main finding of the study by Coricelli and Nagel (2009) is that the mpFC clearly distinguishes high- vs low-level of strategic reasoning, thus encoding the complexity underlying human interactive situations.

The pattern of brain activity in the right and left lateral orbitofrontal cortex and in the dorsolateral prefrontal cortex suggests a substantial jump in complexity when going from first to second level of reasoning. This might be responsible for the observed limited step-level reasoning, either because subjects are not able to make this jump or because they believe that not everybody else is able to make this jump. This result provides a new interpretation that should be implemented in game theoretical modelling. This important difference has never been discussed in the experimental economics literature on strategic reasoning. Instead, the main difference has been thought to be between random behaviour and higher level; mainly because level 1 contains already best reply structure, a fundamental concept in economic theory. However data from Coricelli and Nagel (2009) show that the main discontinuity

is in the belief about other's behaviour as naïve or random behaviour (the underlying belief of level 1 players) vs. belief of best reply behaviour (level 2 or higher).

Notably, the focus of activity in the mpfc (peak MNI coordinates, $x = 0, y = 48, z = 24$; related to higher level of reasoning in our game) coincides with the focus of activity related to degree of thinking about how own behaviour can influence others' behaviour, as reported in a recent study (Hampton *et alii* 2008). In the study by Hampton *et alii* the activity in the mpfc is found when contrasting two dynamic models of choice in a repeated competitive game. One based on updating own strategy based on other's past choices, giving best response to the frequency play of actual behaviour, is essentially our level 1 thinking. A second, more sophisticated type, assumes that subjects considered the effect of their own past choices on other's behaviour (influence). The contrast therefore is analogous to the difference in the beauty contest game between level 2 (or higher) and level 1 of strategic reasoning. Thus, the mpfc encoding the effect of our choices on others' thought and behaviour is the neural signature of high level of strategic reasoning (level 2 or more). The main difference between these two studies are that in Hampton et al. subjects observed others' behaviour over time and need to respond to it, while in our study the subjects need to model also the choices of the others. The brain does not seem to distinguish between these two data sources. Taken together, the results of these two studies represent the first close link between adaptive learning and levels of reasoning.

Rational game theory only predicts equilibrium play, supposing common knowledge of rationality – everybody is rational and thinks that everybody else is rational, and so on. However actual behaviour deviates from equilibrium. In fact, humans use bounded rational strategies or cognitive hierarchies to mimic optimal behaviour. Thus, people behave differently based on different beliefs about others' behaviour. The results of our study demonstrate that much of the variation in strategic behaviour lies in individuals' different attitudes towards others. Crucially, behaviour that was based on more self-referential thinking resulted in a larger deviation from rationality. Thus, people who are socially and strategically more intelligent are likely to reason in a less self-referential way.

This paper should be seen as a contribution to McCabe's statement:

Herbert Simon's research on bounded rationality (Simon 1957) implies that strategies are likely to be encoded in the brain as a mapping from partitions of circumstances into partitions of actions together with inferential (Holland *et alii* 1986) and reasoning mechanisms (Gigerenzer and Selten 2001) that modify and scale these partitions. To understand how such encodings and mechanisms are formed requires both a top down approach using experimental methods [experimental beauty contest] and

strategic models from economics [cognitive hierarchy model] and a bottom up approach using experimental methods [fMRI beauty contest] and computational models from cognitive neuroscience.

With many experiments on the beauty contest game mathematical models of cognitive hierarchy have been developed with which we identify behaviourally different types of level of reasoning. In Coricelli and Nagel (2009) given our design and the simplicity of the structure of the game we identify behaviourally Level 1 and Level 2 and higher Level types and find also differences in brain activity in several areas corresponding to the different behavioural types. The brain activity analysis also clearly distinguishes between the computer and the human condition in theory of mind areas, which indicates that facing humans requires a higher structure of complexity in thinking than facing a computer program. We hope that with our analysis we can give a road map for more complex economic experiments in which the behavioural results cannot clearly identify different levels of reasoning. Then together with brain activities one might in the future structure a behavioural cloud in such a way that different level of reasoning types can also be distinguished if they are indeed present. This should help to advance our ability to interpret brain activity in terms of cognitive complexity.

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