J Bioecon (2008) 10:165–192
DOI 10.1007/s10818-008-9038-5

Making economic sense of brain models: a survey and interpretation of the literature

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Published online: 20 July 2008

Abstract Neuroeconomics draws attention to motive forces that are ignored in the standard framework of economic theory. The present paper develops a conceptual approach that, similar to Pennings et al. (Journal of Bioeconomics 7: 113–127, 2005), tackles the issues at the systemic level by analyzing and modeling the brain processes that decide on behavior. It takes as the basic unit of analysis potential stimulus-response actions which—when selected—become actual behavior. The objective of these potential stimulus-response actions is to increase utility. At any moment of time, several of these potential actions compete with each other for the privilege of becoming actual behavior. This competition can be modeled on the basis of economic principles. The behavior that materializes may cover the range from the rational to the foolish, depending on which of the potential responses gathers the greatest emotional strength. The emotional strength of a potential response, in turn, is determined by the individual's past experience and her capacity for rational action. Given that the objective is always to increase utility, it can normally be expected that the more or less rational dominates the foolish, but this need not always be the case. Which potential actions become behavior in a concrete instance is decided by a mechanism implemented by the basal ganglia, a structure in the brain serving as the action selection mechanism. The insights provided by this approach afford coherent explanations of behaviors that are not readily explicable by the standard approach of economic theory.

Keywords Neuroeconomics · Economic model of brain processes · Processes of decision-making in the brain · Neuroscientific basis of economic behavior

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JEL Classification A12 · D01 · D87

1 Introduction

The new field of neuroeconomics has the potential of subserving all the various styles of economic analysis, despite the reviews of Camerer et al. (2005) and Zak (2004) that see it primarily in support of the behavioral and evolutionary camps. Leading figures of new institutional economics such as North (1994), Williamson (2000) and Coase (1978)[1] also look to the cognitive sciences to throw more light on the foundations of people's economic behavior, and a neoclassical economist like McFadden (1999) recognizes that there are new (neuroscientific) measurements that challenge his preferred model. More positively, neuroeconomics may be able to inform about the extent of consistency of the usual rationality assumptions with people's cognitive processes. There is thus the potential that this new branch helps to bridge the gaps between these different schools of economic thought.

The present paper hopes to contribute to this development by drawing together insights from the cognitive sciences that focus on the underlying springs of behavior and by giving these insights an economic interpretation. The starting point is that brain processes consist of exchanges between billions of neurons that can also be thought of as constituting an economic system, where this system obeys laws of scarcity and value and behaves according to and cost-benefit relations. If this is so, there should be discernable in the brain a structure by which these economic processes are governed. There does, indeed, exist such a structure functioning in terms of demand for and supply of behavior, different technologies with which to realize this behavior, competition, and a mechanism reminiscent of an auctioneer that determines what actual behavior will occur.[2] The contribution is seen to be two-fold. On the one hand, the proposed approach may help to explain activities in the brain by applying economic methodology. On the other hand, it may contribute to a better understanding of people's actual economic behavior. From the first perspective, the individual as a unique 'single-minded' entity dissolves, and behavior materializes at each moment of time as the sum of the outcomes of neural processes without any necessary reference to such an entity; from the second perspective, the individual as the acting entity is again assumed whose behavior however can be explained in terms of these processes. The analysis will be mostly from the first perspective, but there will be a shift to the second point of view toward the end of the paper.[3]

[1] Coase refers here to socio-biology, not neuroscience.

[2] An anonymous referee recommended that the sense in which these economic terms are used in the paper be clarified from the outset. The term 'demand' is used here more in the sense of operations research as 'demand placed on a system' to fulfill a particular task by one of several available means, and the term 'supply' is defined as the ability of the system to provide several such means. The other terms have their usual meanings.

[3] The question how the individual as the acting entity—supposedly with all the attributes of an independent self—emerges out of the sum results of brain processes, as described in the text, is a hotly debated question in philosophy of mind. For the interested reader, Libet et al. (1999) is a good start. For an economist it is safest to evade the question and simply assume that it makes sense to argue at these two levels of analysis.

One salient feature in the model is the pervasive role of emotions as expressions of changes in utility. An emotion reflecting such a change in utility may be caused as much by an event presaging, say, the consumption of a good as by the actual consumption. Emotions occur, both due to the consequences of actual behavior as well as due to the consequences expected of stimuli and the behavior these stimuli will induce. They are both output of behavior and necessary input to it so that desired expected consequences come about. Another feature is the large scope of stimulus-response driven actions, not only in what is normally considered rule-based or habitual behavior but also in the execution of the very act of thinking, deliberation and reasoning. From the point of view of the deciding brain, there is no substantial difference between motor action on the one hand, and deliberation or thinking on the other, either is a behavior[4] that the brain decides on—in the sense whether it is to occur or not—by using the same mechanism. What makes deliberation different is that it is an activity that does not necessarily lead directly to desirable ends but does this indirectly, it being an intermediate activity that may lead to better decisions and rules for later action. Deliberation may occur in harmony with other activities, but may on occasions have to compete with and for its success impose itself on such other activities. Consistent with this view, there is then a nexus of brain activity where the competition between the different demands for activity placed on the organism is resolved, this nexus being the basal ganglia, a group of subcortical structures in the brain.

This is a descriptive model of the productive processes in the brain that are responsible for behavior. It provides a framework within which these activities can be organized following the logic of economics. It is a 'macro' approach given that a micro approach would here imply the modeling of individual circuits and neurons. Like macroeconomics, it looks at interactions between different broad types (aggregates) of activity, for example, by likening deliberation to investment and considering motor actions as behavior directed most often toward immediate goals thus being akin to consumption. It provides a platform from which to look critically at questions of efficiency, welfare, and growth of the individual whose brain processes are modeled.

Pennings et al. (2005) also look at how the brain arrives at decisions. Their article is on the same level of analysis in that it looks at brain processes that decide on behavior but their model is about how the neo-cortex responds to external stimuli to arrive at plans for action. In the present paper the emphasis is on the mechanism, implemented by the basal ganglia, that sees to it that out of an array of competing potential responses, a particular one is picked as the winner. The two pieces of work are complementary in aiming to provide a partial answer to the question raised by McFadden (1999, p. 31) as to 'how far ... economics (will) have to travel to reach solid behavioral ground.'[5]

The paper is organized as follows. Section 2 contains a brief review of results from the neurosciences. Section 3 develops the model that gives these results an economic interpretation. Section 4 provides a discussion of where the model could fit within the canons of economic theory and modeling, and outlines, as an example, how it may

4 From a somewhat different vantage point, Overskeid (2000) also concludes that thinking is behavior.

5 Pennings et al. (2005) put the question at the very beginning of their article.

contribute to an understanding of trust in economic relations. Section 5 provides a summary and conclusions.

2 Background from the cognitive sciences

The relevant literature is large and includes biological neuroscience as well as work in computational psychology, artificial intelligence (AI) and philosophy of mind. Generally accessible sources from a biological perspective are Damasio (1994, 1999), LeDoux (1996, 2002), and Pinker (1997); textbooks are Gazzaniga et al. (2002) and Purves et al. (2004). From a theory of mind point of view, the books by Dennett (1987, 1991, 1996) are very instructive. These sources deal with the brain in a broad context but do not provide the kind of specific structural information necessary to integrate insights from the neurosciences into economic analysis. The book that does this is *The Brain and Emotion* by Edmund T. Rolls (1999, see also Rolls 2000) in that it lays out the role for emotions that is at the basis of the theory developed here. The insights regarding the functions of the basal ganglia are both from Rolls and a number of other researchers that will be given due credit as we go along.

2.1 Rolls'(1999) model of emotions and the basal ganglia

From the vast universe of the brain,[6] Rolls focuses on those structures and functions that are instrumental in determining behavioral output. These structures include the prefrontal cortex, several nuclei of the limbic system, in particular the amygdala, as well as the subcortical group of the basal ganglia which, because of the close functional interaction between them, are collectively referred to as the basal ganglia. Sharp distinctions are difficult but are made here for the sake of simplification and to bring into relief the aspects that this analysis intends to focus on. Thus it is assumed that all other brain structures are either involved in purely autonomous behavior, which are not subject to the mechanism discussed, or are involved in preparing sensory material to be acted upon, or are part of the circuits preparing for and carrying out actions, and therefore lie either before or behind this mechanism.

Central to Rolls' argument is that basically behavior[7] consists of responses to stimuli that predict either rewards or punishments, and that therefore the behavior is either one of approach or avoidance depending on what the stimulus is like. These behavioral

[6] In part of the literature the analysis is conducted in terms of the 'mind' instead of the 'brain'. The position taken here is that, as it were, the production machinery is the brain, and since this is primarily a discussion of production processes, it will therefore be in terms of the brain or its units. The mind, following Clark (1999, p. 289), 'is the brain in action', and according to Pinker (1997, p. 21) is 'what the brain does', which in both cases would make the mind an output of the brain, i.e. part of the behavior to be explained.

[7] For Rolls, and neuroscientists in general, 'behavior' is that of animals of which humans are one species. Here the reference will always be to human behavior. Conclusions drawn from brain research with animals are considered pertinent for human behavior when the structures involved are also present in the human brain. In respect of the brain structures considered in the text, this is true for many mammals, in particular primates. Human brain activity can now also be assessed with new non-intrusive methods such as functional magnetic resonance imaging (fMRI) or positron emission tomography (PET); see in particular chapter 4 of Gazzaniga et al. (2002).

tendencies of approach or avoidance are genetically pre-programmed or, in humans to a very large extent, are acquired through a process of learning that associates stimuli with pleasure or punishment. Stimuli come in the form of prospects for food, drink, sex, pain, comfort or discomfort, someone's smile or frown, money, the vision of solving a mathematical problem, and many others, positive and negative (see Rolls 1999, p. 272). Formally Rolls classifies these stimuli as reinforcers and by doing so is able to represent their effects on a continuous scale from very negative to very positive, passing by intermediate values including indifferent (equal on the scale to zero).

Emotions play a major role in this scheme. They are the states produced by events, either external events impacting directly on the organism or brought about by a response to an external event. They reflect the 'value' assigned to events, both those that are currently experienced and those that are expected to be experienced as a consequence of actions. Values as expressed by emotions are a requirement for identifying the proper response to a situation and are thereby a necessary ingredient for each and every action by the individual. Emotions may be considered the representations of a person's wellbeing and are thus an empirical correlate to economists' concept of utility.[8]

The orbitofrontal cortex and the amygdala are, according to Rolls, the two brain structures that are most heavily involved in this process. The orbitofrontal cortex is a subdivision of the prefrontal cortex, sitting right behind the forehead. It is responsible for the higher executive functions and is the unit having the role of identifying the set of potential courses of action. It gets the requisite input for this from many parts of the brain, for example other divisions of the prefrontal cortex, but in particular from the amygdala which, sitting as part of the limbic system at the inner side of the cerebral cortex, has a prominent role in understanding and storing the emotional significance of things.

The basal ganglia are the third important structure in Rolls' theory. They are an evolutionary old group of nuclei at the base of the brain which, considered as a unit, have long been implicated in controlling motor behavior. There is currently a consensus emerging, however, that they play a much larger role and that they are exercising the function of a selector of *all* behavior, and that they decide which of several competing actions are going to be performed. They do not initiate actions but, as it were, release the brakes on some action and keep a tight rein on others.[9] In Rolls' theory they mostly still play the old role but the newly identified function is mentioned here as it will become an important part of the ideas discussed further below in this section.

Figure 1, only slightly modified from Fig. 9.4 in Rolls (1999), shows how behavior is generated. Disregarding reflexes caused directly via brainstem and spinal cord, we

[8] Rolls' ideas on emotions are both criticized and given support in an Open Peer Commentary (2000). I do not have the knowledge to take sides in this debate. For the purpose of the paper, it is assumed that whatever valid criticism there is of Rolls' theory this would not invalidate its use in the present context. Besides, the relevant argument in the paper does not rest on Rolls' theory alone.

[9] In the neuroscience literature, these functions are often discussed in terms of the individual structures of the basal ganglia, which are the striatum, itself composed of the caudate nucleus and the putamen, the globus pallidus, the subthalamic nucleus, the substantia negra, the nucleus accumbens and some more, depending on context and author. Although these structures are not all involved to the same extent in these functions, the broader term is used here to avoid unnecessary detail.

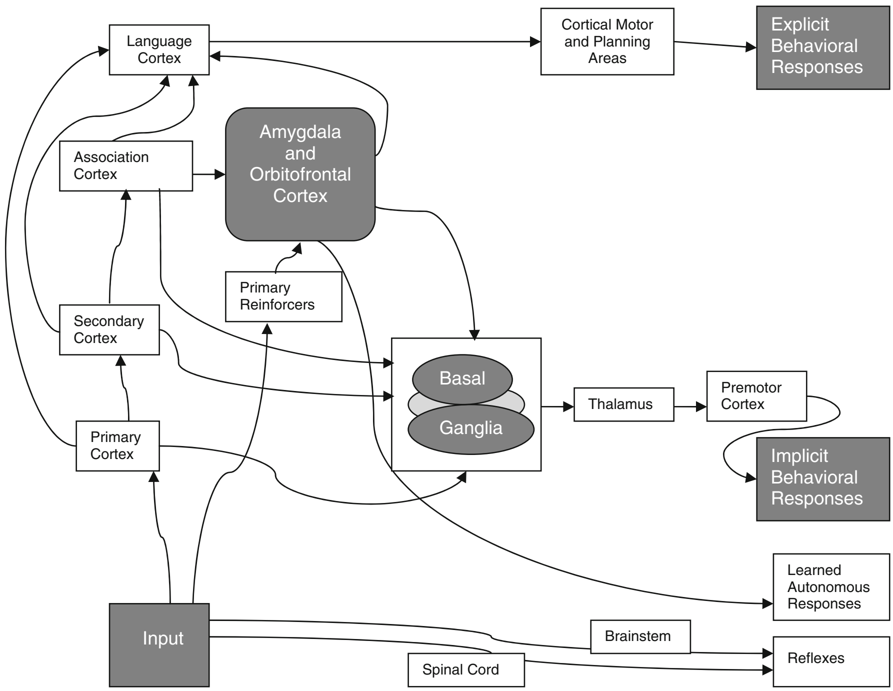

Fig. 1 Rolls' dual routes to the initiation of action (adapted from Fig. 9.4 in Rolls' (1999) book, *The Brain and Emotion*). Original legend for Fig. 9.4 in Rolls' (1999) book: 'Dual routes to the initiation in response to rewarding and punishing stimuli. The inputs from different sensory systems to brain structures such as the orbitofrontal cortex and amygdala allow these brain structures to evaluate the reward or punishment-related value of incoming stimuli, or of remembered stimuli. The different sensory inputs allow evaluations within the orbitofrontal cortex and amygdala based mainly on the primary (unlearned) reinforcement value for taste, touch and olfactory stimuli, and on the secondary (learned) reinforcement value for visual and auditory stimuli.... One route for the outputs from these evaluative brain structures is via projections directly to structures such as the basal ganglia (including the striatum and ventral striatum) to allow implicit, direct behavioral responses based on the reward or punishment-related evaluation of the stimuli to be made. The second route is via the language systems of the brain, which allow explicit (verbalizable) decisions involving multi-step syntactic planning to be implemented'

note that there are two routes to action passing through the combination of the AOC complex and basal ganglia. Over the first route, referred to by Rolls as 'implicit', sensory input signals run via the primary, secondary and association cortices to the AOC complex, to the basal ganglia, and then via thalamus and premotor cortex to behavior. The second 'explicit' route involves the language systems of the brain, called into action by the AOC complex, which make explicit (verbalizable) decisions possible through multi-step syntactic planning in the cortical areas, and thus represent the mental capacity for reasoning. What causes a particular stimulus to provoke either an implicit or an explicit response, or several of both, competing with each other to be selected, while other external events (potential stimuli) are disregarded, lies in the individual's past experiences and is for the present purposes considered as given.

Rolls' approach is used here because it gives emotions a role that can easily be linked to economic concepts and it is readily accessible to non-neuroscientists. His results on emotions are also broadly consistent with research showing that the brain values events and goods in terms of the neurotransmitter dopamine. The work by Shizgal and Conover (1996), Shizgal (1997), Montague and Berns (2002), and McClure et al. (2004) is particularly relevant. What these researchers argue is that there is a common unit in terms of which the relevant neural systems evaluate all sorts of different awards and punishments so that immediate comparison of the value of different experiences and stimuli is made possible. The work of Montague and Berns, and McClure et al. claim that it is value that they have measured.[10] They also implicate directly the basal ganglia in their study. Shizgal-Conover, in turn, relate their measurement directly to utility.

Relating the findings of the work of Montague and Berns, McClure et al., and of Shizgal-Conover to those of Rolls, and assessing their work in terms of the objective of this paper, it appears that the emotions of Rolls, the valuations of Montague and Berns, McClure et al., and the utility of Shizgal-Conover, are pretty close to the concept of utility as economists use it.

2.2 Complementing Rolls' model

Rolls' second route to action, once taken, is not supposed to pass by the basal ganglia (see Fig. 1), which means either that whatever competition there may be for behavior via the first route would effectively be shut out as soon as the second route has been engaged, or that there may be incompatibilities. Rolls actually assumes the second possibility but believes that the incompatibilities would reduce to inconsequential noise. This, however, does not appear to be consistent with the evidence that has been emerging in the work of a number of researchers. The basal ganglia, according to this view, also control the processes going on in the language cortex and in the planning areas; they are thus the brain structures that decide which behavior will take place, be it inwardly directed mental action or outwardly directed motor action. In a summary of findings up to the time of their writing, Brown et al. (1997) implicate the basal ganglia in having a role in cognitive as well as motor functions. They state: 'In addition to primary sensorimotor functions, the basal ganglia may serve an executive function in the brain for aspects of perception, adaptive motor control, working memory, flexibility of thought, and initiative and drive.' Redgrave et al. (1999, p. 1099) then expressly identified the basal ganglia as *the* brain structure involved in final decision making, proposing 'that the vertebrate basal ganglia have evolved as a centralized selection device, specialized to resolve conflicts over access to limited motor and *cognitive* resources. Analysis of basal ganglia functional architecture and its position within a wider anatomical framework suggests it can satisfy many of the requirements expected of an efficient selection mechanism.' [Emphasis added]

Purves et al. (2004, p. 432), in a chapter on the control of motor movements, dedicate a special box to the newly emerging functions of the basal ganglia. They identify

[10] McClure et al. (2004, p. 261) hypothesize that 'the brain may process rewards along a single final common pathway in the form of a kind of common neural currency' and that '(f)unctionally this may reveal an important insight into how reward information is processed in the brain: a common network allows widely different rewards to be directly compared for the purpose of choosing between possible courses of action.'

anatomical loops similar to the motor loop described in that chapter but terminating in non-motor regions: 'These "non-motor" loops include an "executive" loop involving the dorsolateral prefrontal cortex and part of the caudate ... and a "limbic" loop ... involving the cingulate cortex and the nucleus accumbens. The similarity of these additional loops to the traditional motor loop suggests that the non-motor regulatory functions of the basal ganglia may be generally the same as what the basal ganglia do in regulating the initiation of movement. For instance, the executive loop may regulate the initiation and termination of cognitive processes such as planning, working memory, and attention.' Note that in the quote a 'limbic' loop is identified which we can presume to correspond largely to the one in terms of emotions discussed by Rolls and taken up in the preceding subsection. Finally, we refer to Hecht-Nielsen (forthcoming) who, although his work does not focus on the basal ganglia, explicitly recognizes their role in motor and higher cognitive functions. He notes that there are '... higher-level action commands, such as delivery of a *candidate* movement or thought plan to the basal ganglia for rapid evaluation and approval. If approved, the candidate action command flows through and proceeds via the thalamic ventral lateral nucleus right back up to a different cortical region, where it activates a token which immediately launches that command for unconditional execution.'[11] Note that a token is an unit in Hecht-Nielsen's analysis of thinking. As we do in this paper, Hecht-Nielsen considers both thoughts and movements as actions and actually refers to them as 'siblings'.

It cannot definitely be claimed yet that there is a consensus in neuroscience about the role of the basal ganglia as *the* selection device (see in particular Kilcross and Coutureau 2003). It seems to me, however, that most researchers working in the field tend toward this view and that it is therefore likely that a position like the one presented in this paper will in the end prevail. Luu and Tucker (2002), Dalgleish (2004), and Daw et al. (2006) present diverging opinions more by way of different emphasis than by way of rejecting the views discussed.[12]

In Fig. 2 we modify Rolls' description of how behavior is generated in one significant way. The outward link of the second route is eliminated, i.e. the one whereby signals via the language cortex and the cortical motor and planning are sent directly to structures causing outwardly directed behavior. Instead, signals carrying the stimuli generated in the planning and thinking areas of the prefrontal cortex loop from these areas back to the AOC complex to be loaded with emotional strength, before being passed on for appraisal to the basal ganglia.

Each time when such stimuli reach the basal ganglia, they are scrutinized as to whether they should further prevail in competition with other signals; once being

[11] The quote is from Hecht-Nielsen's manuscript 'Thinking' (October 2, 2003 and accessed at http://inc2.ucsd.edu/pdfs/ on 28 December 2006). When asked how to cite the piece, Prof. Hecht-Nielsen kindly referred me to the entry 'Confabulation Theory' in Scholarpedia and to his book (Hecht-Nielsen, forthcoming) where his ideas on the matter are developed. I quote the above passage because it very succinctly brings out the closeness of his ideas with those in the present paper.

[12] See also Baxter and Murray (2002) who take a position like the one in this paper regarding the role of the amygdala, and at the same time attempt a reconciliation of diverging points of view.

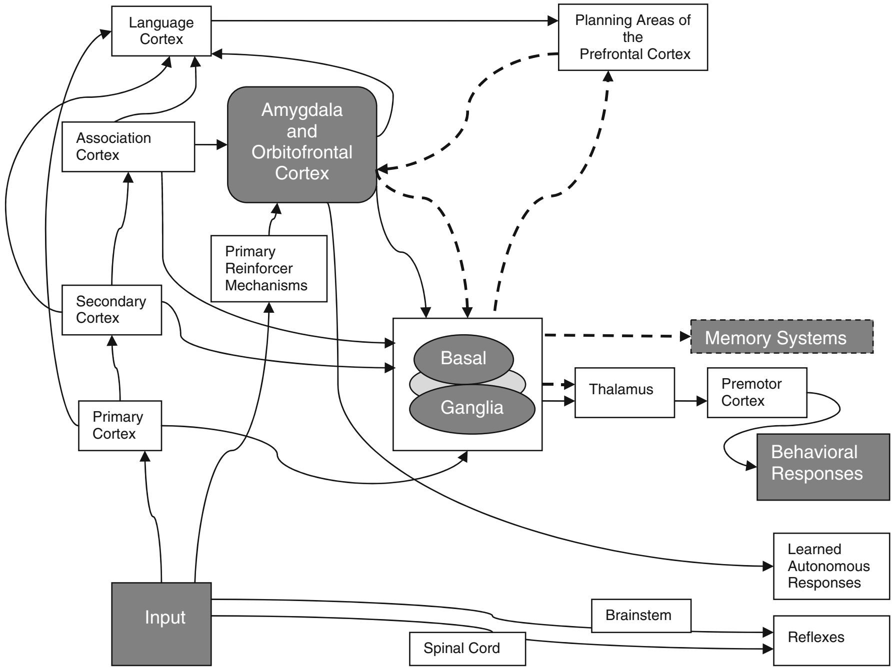

Fig. 2 Routes to the initiation of action with an enhanced role for the basal ganglia (adapted with changes from Fig. 9.4 in Rolls' 1999 book *The Brain and Emotion*). In comparison to Fig. 1, the pathways of the explicit route to action are modified as indicated by the broken lines. The one from the Planning Areas of the Prefrontal Cortex to Explicit Behavioral Responses is eliminated and instead one from the Planning Areas of the Prefrontral Cortex back to the Amygdala and Orbitofrontal Cortex complex and then to the Basal Ganglia is introduced. From the Basal Ganglia, depending on the content and quality of the signal and what the Basal Ganglia have decided on it, the signal may travel either: (i) back to the origin, i.e. the Planning Areas of the Prefrontal Cortex, and (ii) to some Memory System, or (iii) to the Thalamus and Premotor Cortex for some outwardly directed Behavioral Response. It may also, what is not shown in the Figure, simply be dropped

successful, they are sent back to the planning areas for further deliberative steps. If deliberative activity has come to a successful end, i.e. with a result to be acted on, the cortical planning areas will send corresponding signals via the AOC complex to the basal ganglia which will then switch to the matching course of action—be it only that the rule for action is committed to memory to be resurrected following an appropriate stimulus and acted upon at a later time. The proviso for the consequent behavior actually to occur is that other competing signals are not strong enough to prevent this to happen. It would, however, not be uncommon that after successful deliberation a different course is, nevertheless, engaged where the basal ganglia react at the critical moment to signals with greater emotional strength.

When the role of the basal ganglia is interpreted this way, it is guaranteed that in healthy individuals there is, at any moment of time and with respect to the same stimulus, always one sinlge behavior and the individual does not attempt to carry out simultaneously different behaviors because in the brain different requests for action try to gain dominance by using different pathways.[13] In comparison to Rolls' interpretation the present paper takes the view that in terms of neural processes there is only one route to action, in the sense that each behavior is controlled by the AOC complex and, in the final analysis, by the basal ganglia. This means that Rolls' explicit actions, involving thought, deliberation and mental activities in general, are in respect of how they come about no different than his implicitly determined motor actions. Rolls' implicit route involving the AOC complex and the basal ganglia is the really essential mechanism; the explicit route is just a name for a subset of actions that, from the perspective of this paper, have special status only because of their role in preparing the organism for future action. The distinction between explicit and implicit action in the sense Rolls uses it will not play a role in the remainder of the paper.

It may be helpful to give concrete real life examples of actions for which the basal ganglia would have been decisive one way or the other. Some are listed in Table 1; they are based on observations made by the author.

The examples listed are all 'small' in the sense that they concern very brief episodes in every day behavior. This should, however, not be surprising as 'big' decisions, like buying a house or embarking on a particular business career, are normally the consequences of many small decisions. It is also possible that one single such decision has momentous consequences, as would be the case with example (iii) in the Table: if it were decided to collect no further information, and if this decision were not revisited later and an investment were carried out, which might not have been made with the additional information, and if it then proved to be disastrous. Example (ii) shows that different candidates for responses to a particular stimulus may be competing that would appear very unlikely and of which one would not be aware if it were not for such embarrassing accidents. From this it can be deduced that the basal ganglia are constantly busy selecting from a whole array of possible—appropriate and inappropriate—responses those that are 'best' to fit the given stimuli, mostly doing this in some satisfactory way and erring grossly only on rare occasions.

2.3 The role of memory systems; procedural memory and the basal ganglia

One can distinguish between four types of long-term memory: the perceptual representation, declarative, stimulus-reinforcement (emotional), and procedural memories.[14] The perceptual representation system is of no interest here since it is preliminary to declarative memory. Declarative memory is about facts and events of the past; the prefrontal cortex is implicated in it as well as other structures of the

[13] There are, of course, many instances where there is inconsistency in behavior, Parkinson's and Huntington's Diseases and Obsessive Compulsive Disorders are obvious cases in point. It is known that these conditions are the results of basal ganglia malfunctions. Also minor cases of malfunctions can be observed in healthy humans that represent, as it were, slips in the working of the basal ganglia.

[14] Short-term memory need not concern us here as it is part of the machinery of the prefrontal cortex responsible for thinking, deliberation etc. On memory in general, see Packard and Knowlton (2002), chapter 8 of Gazzaniga et al. (2002), and in particular University of Toronto neuroscientist William Milgram's manuscript 'Learning and memory: systems and processes' that was accessed in 2006 at www.scar.utoronto.ca/~milgram/nroc61.

Table 1 Examples of actions being 'decided upon' by the basal ganglia

(i)	A password has to be entered in order to access a computer. The choice is from two such passwords, depending on whether it is the office computer or the one at home. This is usually done without pausing as the right response normally comes forward automatically. It then occasionally happens that the password for the other computer is entered. The interpretation is that the basal ganglia being confronted with the stimulus 'enter password' is, because of some interference, prevented from properly finishing its evaluation and lets the wrong password 'get through'. The interference may be the competition for action in response to the next stimulus, like 'making other preparations to be ready for work once the computer is booted up.'
(ii)	Instead of an expression of sympathy when meeting an acquaintance who deplores the death of a family member, a congratulatory expression slips out. There is no reason to assume a Freudian slip. Out of the prepackaged set of responses for showing concern for another person, the basal ganglia, due to some interference, are led to pick the wrong specimen. This has actually occurred to a colleague of the author.
(iii)	Information for a business decision has been assembled. After its evaluation there are reasons to argue that additional information should be gathered. The competing response is to agree to stop pushing for this additional effort and declare the information base as sufficient, which is enhanced by the urgings of other persons involved in the decision process who believe that the case is now ripe for action. The candidate response 'arguing for more information gathering' may have to acquire high emotional strength (value) for it to 'convince' the basal ganglia to let this response have its way.
(iv)	In consulting, there is sometimes value in doing a job in the 'quick-and-dirty' way (even the client may ask for it if speed is of the essence). Given the predilections of the consultant, urges (candidate responses) to do the job 'properly' may at any moment get in the way and may be approved by the basal ganglia despite deliberate efforts to always act as initially planned.
(v)	The stimulus is the opportunity of conversation with an interesting person. Two responses compete with each other, the one being to ask the person a loaded question, the other to engage in non-controversial small talk. Deliberation says that the question should be asked, the visceral (stimulus-response) reaction would be to carry on the small talk and refrain from asking the question for fear of being rebuffed. It is revealing that when the question is then actually asked, this very fact may come at some surprise as apparently no explicit decision to ignore the fear of being rebuffed preceded the act. Without that any awareness of this happening is created, the basal ganglia then opened the gate for that response to take place.
(vi)	A paper is being written. An idea has been formulated and typed into the word processor. Two stimuli compete with each other for attention: go over the paragraph and check whether the idea has been formulated correctly and clearly enough, or move on to the next idea because this advances the paper writing process. It would appear rational to do the second as the first job can always be done later. Nevertheless, the urge for punctiliousness now may have the greater emotional strength and be successful to have the basal ganglia move in its favor.

cerebral cortex and the limbic system, in particular the hippocampus. The stimulus-reinforcement memory, as the name implies, provides the information required for the evaluation of stimuli in terms of their significance for reward and punishment; the amygdala is primarily involved in it. We will turn to the roles of declarative and stimulus-reinforcement memories toward the end of the section. Of foremost interest at this moment is procedural memory, which is the memory that retains the knowledge about skills and habits, i.e. how to do things without having to reflect about them. The focus so far has been on the mechanism for selecting between alternative candidate plans for action on the basis of relative valuation of stimuli, in which it was found that the basal ganglia play an important role. What has not been considered is how in this process the *competence* available to carry out the selected action is taken into account. The point is that procedural memory, the locus where the memory of these competences are stored, is also largely dependent on the basal ganglia.

There appears to be no controversy in the literature about the general involvement of the basal ganglia in the learning and storing of procedural knowledge (see, for example, Phillips and Carr 1987; Brown et al. 1999, 2000; Graybiel 2000; Packard and Knowlton 2002; Ashby and O'Brien 2005) although it appears difficult to pin down what the specific task of the basal ganglia in procedural memory actually is. Most of the empirically oriented studies seem to restrict themselves to reporting that whenever actions involving procedural learning or the retention or retrieval of procedural knowledge are observed, activity is also recorded in at least one of the units of the basal ganglia. One relevant statement is that the basal ganglia perform the task of information integration which suggests that they provide the locus where the information about skills and capabilities are made comparable (Ashby and O'Brien 2005). This is knowledge which is certainly important in situations where it must be decided on which of the available skills is most appropriate to respond to a stimulus. From the perspective of economics, it would make good sense to let the unit that decides on action have immediate access to the means by which the ends are to be arrived at. In this way not only relative values of alternative actions but also the chance of success of each action could most efficiently be assessed before action is actually decided on. This is the perspective taken from here on in the remainder of the paper.

Stimulus-reinforcement memory will, in the following, be referred to as the place where the results of learning regarding the value of things and their potential contribution to the organism's well-being are being stored. Like procedural memory it comes about implicitly, i.e. without the individual necessarily being aware of it. Declarative memory, in turn, is like the library where all explicit knowledge of the organism is stored. Its content is being used for deliberative behavior, but it should be suspected that like the two other memories considered it also contributes to the selection of stimulus-response candidates for action. To understand this latter relationship, however, the results of a lot more neuroscientific research is needed.

2.4 Consciousness and perceptions

In the introductory section, the present approach to brain processes was likened to macroeconomics since it also puts an emphasis on particular aggregates in the brain that merit heightened attention. These turn out to be outwardly directed (motor) actions on the one hand, and inwardly directed (deliberative, thinking, mental) actions, on the other. Again, as in macroeconomics, certain not unsubstantial phenomena are kept in the background. They are considered to lack the specific relevance to become part of the explicit modeling.

One of these phenomena is consciousness. Since consciousness is commonly considered a very important aspect of human nature, neglecting it here calls for an explanation. In psychology and philosophy of mind, consciousness is seen to assume a number of roles. When an organism is conscious, the minimum that one can attribute to it is that it is awake and more or less alert. This is a state that humans share with many animals; it is maintained automatically except when the individual changes that status and goes to sleep. Like other very basic functions of the body, it does not belong to the relationships discussed in this paper. Two other functions are consciousness in the sense of access to one's mental representations (thoughts) and consciousness in the sense of feeling what it is like to be a human being, also referred to as phenomenological consciousness or sentience. The last of these two types will also not be of interest here. It is hotly debated in philosophy of mind but here it may be considered as part of utility experienced by an individual and thus generally be subsumed under this term. The type of consciousness of interest is the access type, whereby access to the content of parts of the brain is provided, allowing the organism to focus on this content, to reflect on it and the consequences that would follow from it, and even reflect on these reflections, enabling the organism to adapt its reactions to stimuli in a way it would otherwise not be able to do.[15]

It is thus conscious attention to a particular activity of the brain which is relevant for the purposes of this paper. Actions that benefit from it have a particular quality, presumably a quality that enhances the effectiveness of their execution. Accordingly, conscious attention is here regarded as the expression of a skill that is given credit for accomplishments that could not be mastered without this ability—but no more. It would therefore be akin to the category of capabilities discussed in the preceding subsection.

Consistent with this perspective, researchers have established that the basal ganglia are involved, too, in the control of this type of consciousness; one observer noting the role of the basal ganglia (and the prefrontal cortex) in determining this function of consciousness, refers to this ability as a sort of mental muscle. The basal ganglia thereby act as a selection device for conscious access to particular mental processes, the same way as they do for actions, selecting those perceptions and thoughts that have to have preeminence. 'Control of motion and conscious attention are similar: we decide to think about a menu plan in much the same way we decide to pick up a pot' (Hibbard 2002, p. 95). This interpretation emphasizes the service function of consciousness (of the access type) and implies that beyond this it has no outstanding role to play in the present analysis.

Like consciousness, perception is another important part of mental activity not accorded any particular status in this paper. It is a constituent part of the stimulus-response mechanism. A particular perception may be considered an intermediate output of the process from stimulus to response, since it is on the basis of how a stimulus is perceived that a response is initiated. Perceptions, however, need to be mentioned because in some of the recent economic analyses (see, for example, McFadden 1999), errors in perceptions are identified as a main reason for deviations of observed economic behavior from that expected by standard theory. Here we note that the perception of a stimulus is influenced by the memory of experiences related to similar stimuli in the past and that, in turn, the value assigned to the stimulus by the amygdala is influenced by these experiences. Obviously experiences can hugely vary between individuals, giving rise to different valuations that in terms of the experiences, and forecasts based on these experiences, may have a subjectively valid basis although on the basis of another 'objective'[16] assessment they may appear otherwise.

15 See, for example, Dennett (1991) and Chalmers (1996).

16 Note that an 'objective' assessment presupposes some kind of teleology on the basis of which it would generally be optimal to behave in a certain way, disregarding particular past experiences associated with

As will be seen, this influence of the amygdala is part, but only part, of the explanation of otherwise puzzling behavior.

3 View from economics: a model

Many of the neural relationships discussed have an obvious economic flavor. There is thus the temptation to place these relationships within a formal framework of economic analysis which this section sets out to do.

3.1 The formal economic model

The quintessential economic assumption maintained is that utility experienced by an economic agent is the measure of success of behavior. In switching to the language of economics, we identify the values assigned to stimuli and to the responses thereto as concrete changes in utility. Responses to stimuli (actions) that are selected and materialize to form behavior aim at producing positive changes in utility. We are interested in an individual's utility as it evolves and is continuously accumulated from one moment to the next. Therefore, the change in utility between two points in time is the variable that needs explaining. Except that changes in utility brought about by behavior be positive, there are no further axiomatic restrictions placed on them.

We focus on the change in utility as it occurs during a very small time interval which will be denoted in the following by Δu_t. This change in utility is brought about by the individual's behavior during the time interval, and by external events beyond her control and having a direct impact during this same time interval. Behavior during any time interval is conceived to consist of the sum of a number of different chunks of behavior engaged in simultaneously. For example, the person might be walking along the sidewalk, holding her dog at the leash, greeting neighbors that pass, enjoying the afternoon sun, being intent on going to the grocer's at the corner of the street to do some shopping, and while she is doing these things, be thinking about how to allocate the salary that she has just received for a week's work.[17]

Formally, we write for this the following functional relationship:

$$\Delta u_t = \Delta u \left(b_{1,t}, \ldots, b_{i,t}, \ldots, b_{n,t}; E_t\right), \tag{1}$$

where the $b_{i,t}$ are the chunks of behavior taking place simultaneously during time interval t and E_t is the set of external events beyond the current control of the individual. A change in utility is shown to be caused during each time slot by the n things the individual is then—simultaneously—engaged in, as well as by the effects of external

Footnote 16 continued
this behavior which might make a different kind of behavior more attractive. Given external constraints, people are often induced to obey rules that objectively are the right ones (see Simon 1996 who forcefully argues this point), but for this to happen the individual has nevertheless to make a subjective decision.

[17] We should note that in this description we go beyond the review in the preceding section where the AOC complex or the basal ganglia were not shown to determine behavior that occurs simultaneously. We consider this, however, as an obvious and plausible generalization to be made.

events then directly enjoyed or endured by her. Utility is here a cardinal quantity, since the literature cited earlier (Shizgal and Conover 1996; Shizgal 1997; Montague and Berns 2002; McClure et al. 2004) suggests that the neural phenomena representing the values assigned to stimuli and actions can in principle be quantitatively measured. Also, we are here comparing concrete changes in utility which, by construction, must be discretely valued. Regarding the dimension of a $b_{i,t}$ it is best to think of it as a an action measured in physical units that through the function $\Delta u(\ldots)$ is transformed into a contribution to Δu_t. This may simply be a movement of limbs to transport the person towards a desirable place; it may be an utterance, either by voice or in writing, expressing a thought; it may also be a neuronal activity by which a thought is created or a perception registered.

Regarding the elements contained in E_t, two aspects need to be noted. Firstly, they are not external in the sense that they come exclusively from outside the agent; they may as well be internal to the agent but external to the system that we are looking at, like the feeling of hunger produced by a body system not considered here. Secondly, they are predetermined but not strictly exogenous as they may be due to some behavior on the part of the individual that occurred at an earlier time. This second aspect makes clear that current utility is, to a large extent, brought about by actions that have taken place in the past and that current actions may primarily serve to bring about changes in utility in the future.

Let us consider behavioral chunk $b_{1,t}$ which in our example is 'thinking hard about how to put together a budget for next week with the salary just received', occurring in response to an stimulus from the organism indicating that this needs to be done. Following Rolls (1999, 2000) and the discussion of the preceding section, a behavior is a function of the reward, i.e. positive change in utility, that this behavior promises, where the effective strength of the reward is determined by the internal evaluation system—the AOC complex of the preceding section—and expressed by a corresponding emotion. So while semantic step by semantic step deliberations are going on, the pull for them to continue must be sustained by a reward in terms of an emotion with the adequate strength, where the reward here is the expectation for the individual to have a stress-free week in terms of availability of resources to buy things. There are competing activities for $b_{1,t}$ to be currently carried out, for example doing the job of deciding on a budget in a most perfunctory way, say leaving it the same as it was last week. Depending on the emotional strengths mustered by competing behaviors, the one or the other has a lesser or greater chance of prevailing. From this follows that the criterion by which an activity is selected is the expected positive change in utility due to a given behavioral response as expressed by the following equation:

$$\Delta u^e_{j\cdot 1,t} = \Delta u_{j\cdot 1}\left(b^c_{j\cdot 1,t}, e_{1,t}; E_t^{-1}\right), \quad j = 1, \ldots, m \tag{2}$$

in which $\Delta u^e_{j\cdot 1,t}$ denotes the expected contribution to utility by candidate activity $b^c_{j\cdot 1,t}$ and the sub-index $j \cdot 1$, $j = 1, \ldots, m$ indicate the number of the various competing alternatives for behavior slot 1. Equation 2 contains, besides $b^c_{j\cdot 1,t}$ as additional explanatory variables, the specific stimulus $e_{1,t}$ and the set of all other external events E_t^{-1}. The variable $e_{1,t}$ is included because each specific event may be somewhat different from any previous one of this type so that if $b^c_{j\cdot 1,t}$ is selected it may not transform the impact of the stimulus in exactly the same way as at earlier occasions. The set of other external events E_t^{-1} has a role as each such set of events will circumscribe the effectiveness of the candidate activity in a particular way.

An activity may be more or less effective as the level of skill with which a particular action can be carried out to reach the intended goal varies between individuals. With respect to a candidate activity, we model this by having a $b^c_{j\cdot i,t}$ be the function of two variables: (i) $\beta_{j\cdot i,t}$, defining the activity as it is perceived by the system to be feasible; and (ii) $s_{j\cdot i,t}$, representing the relevant skill available to carry out this activity, which leads to the following equation:

$$b^c_{j\cdot i,t} = b_{j.i}\left(\beta_{j\cdot i,t}, s_{j\cdot i,t}\right) \quad \text{with } \partial b^c_{j\cdot i,t}/\partial s_{j\cdot i,t} > 0. \tag{3}$$

The greater the skill the greater would be the effectiveness of the activity. No maximum attainable level of effectiveness (or skill) is defined, although for easy every-day skills this may be a reasonable assumption. If the required skill is very specific and difficult to gain perfection, the $s_{j\cdot i,t}$ might substantially vary between individuals.

We now make use of the insight from neuroscience discussed in the preceding section—remembering in particular the role of the basal ganglia—that there exists a ‘supplier’ of behavior in the sense that it determines which activity is to take place, based on the promises of the candidate activities to create value. This mechanism is specified as:

$$b_{1,t} = \rho\left[\left(b^c_{1\cdot 1,t}, \Delta u^e_{1\cdot 1,t}\right), \ldots, \left(b^c_{j\cdot 1,t}, \Delta u^e_{j\cdot 1,t}\right), \ldots, \left(b^c_{m\cdot 1,t}, \Delta u^e_{m\cdot 1,t}\right)\right]. \tag{4}$$

The arguments in the brackets on the right side of Eq. 4 are the m potential candidate behaviors together with the expected changes in utility dependent on them. The function ρ picks the $b^c_{j\cdot 1,t}$ that promises the greatest such change. Equation 4 is thus the system’s decision function. It resembles the Walrasian auctioneer insofar as values are ‘called out’ to it and it determines the winning activity. We note, as an implication of resources being reserved to respond to event 1, that these resources are blocked for use in responding to any of the other events $e_{i,t}$ and therefore all the other behavioral chunks $b_{i,t}, i \neq 1$, to be determined by equations parallel to (4), would have to do without this capacity. This obviously implies simultaneity in the determination of all $b_{i,t}$, $i = 1, \ldots, n$, an aspect that we note but in this exploratory paper do not dwell on any further.

To round up the model, we postulate some plausible relationships regarding how the system determines what particular menu of candidate responses is available for the given stimulus, and how it knows about the skills available to carry out the various candidate actions. These relationships rest on plausibility considerations as relevant research results from the neurosciences are still lacking. The set of candidate responses are considered to be a function of all three memories that were discussed in the preceding section. The stimulus-reinforcement memory proposes the candidate responses for every stimulus and endows them with their emotional values while the declarative memory is needed to the extent that deliberation plays a part in these responses. The procedural memory in turn provides the information on the levels of skill with which the activities can be executed. Letting each candidate response $b^c_{j\cdot i,t}$ be represented by its explanation in terms of Eq. 3, we thus have

$$\begin{aligned}&\left[b_{1\cdot i}\left(\beta_{1\cdot i,t}, s_{1\cdot i,t}\right), \ldots, b_{j\cdot i}\left(\beta_{j\cdot i,t}, s_{j\cdot i,t}\right), \ldots, b_{m\cdot i}\left(\beta_{m\cdot i,t}, s_{m\cdot i,t}\right)\right] \\ &\quad = B\left(M_{st\text{-}r,t}, M_{d,t}, M_{p,t}\right)\end{aligned} \tag{5}$$

where $M_{st\text{-}r,t}$, $M_{d,t}$ and $M_{p,t}$ stand for stimulus-reinforcement, declarative and procedural memories, respectively, and the function B assigns to each $b_{j\cdot i}(\beta_{j\cdot i,t}, s_{j\cdot i,t})$ its value by drawing on these memories. Equation 5 thus summarizes the determination of both the composition of the set of possible responses as well as the make-up of each. In particular the stimulus-reinforcement memory contains the specific memory entries $M_{st\text{-}r,j\cdot i,t}$ which are relevant for determining each of the $\beta_{j\cdot i,t}$ in the set of possible responses, and procedural memory contains the specific entries regarding the levels of skill $s_{j\cdot i,t}$ available to carry out these activities. If the candidate response is of the deliberative kind it would need to be free to use *any* of the whole set of items stored in declarative memory.

Of the memories entering (5) as explanatory variables, it is worthwhile to write down stylized specifications of functions for the stimulus-reinforcement and procedural memories. These explain their contents insofar as there are two types of experiences that would affect them in distinct ways. One type derives from the experience of a relevant event that actually took place, and the other type from a deliberative, reflective activity focused on such an event. Thus for the stimulus-reinforcement memory of a particular activity j in response to a stimulus i we would have

$$\begin{aligned}M_{st\text{-}r,j\cdot i,t} = M_{st\text{-}r}&\left[\left(\Delta u_{j\cdot i,t-1}/b_{j\cdot i,t-1}/e_{i,t-1}\right), \left(\Delta u_{j\cdot i,t-2}/b_{j\cdot i,t-2}/e_{i,t-2}\right), \ldots;\right. \\ &\left. b^d\left(\Delta u_{j\cdot i}/b_{j\cdot i}/e_i\right)_{t-1}, b^d\left(\Delta u_{j\cdot i}/b_{j\cdot i}/e_i\right)_{t-2}, \ldots\right], \quad j = 1, \ldots, m,\end{aligned} \tag{6}$$

where both sets of explanatory variables may in general range over all past periods of the individual's life. The first set consists of actual utility changes experienced in the past relative to the behavior that occurred in response to the relevant stimuli; the other represents past behavior variables, marked with a superscript d for 'deliberative', for which the terms in the parentheses indicate what the deliberative activity is about, i.e. the merits of the i-stimulus/j-i-behavior/j-i-utility relationship. The second set of explanatory variables implies that any stimulus/behavior/utility relationship in the past may have been the subject of deliberation the results of which would then impact on the stimulus-reinforcement memory. For procedural memory we postulate a similar specification for a skill-demanding activity j that can be used to deal with stimulus of type i:

$$\begin{aligned}M_{p,j\cdot i,t} = M_p&\left[b_{j\cdot i,t-1}, b_{j\cdot i,t-2}, \ldots; b^d\left(b_{j\cdot i}\right)_{t-1}, b^d\left(b_{j\cdot i}\right)_{t-2}, \ldots\right], \\ &j = 1, \ldots, m,\end{aligned} \tag{7}$$

where the first set of explanatory variables represent the instances that the skill-demanding activity has in the past actually been applied and the second set, marked with a superscript d for ‘deliberative’, represents the cases that the behavioral skill has deliberatively been attended to, usually with the intent to practice it. The deliberative behavioral variables $b^d(\ldots)_{t-i}$ make clear that stimulus-reinforcement and procedural memories are not only of events in which the stimuli occurred and were responded to but also of additional—mental—events during which such events were deliberatively reflected on.[18]

Declarative memory contains all events and behaviors in the past that have consciously been attended to and which were salient enough to permanently enter that memory. For the purposes of this paper there is nothing specific that we can say on this so that, to be complete, we restrict ourselves to the most general formulation, i.e.

$$M_{d,t} = M_d\left(E^s_{t-1}, E^s_{t-2}, \ldots; B^s_{t-1}, B^s_{t-2}, \ldots\right), \tag{8}$$

where the variables in the parentheses on the right side stand for past events and behaviors and the superscript s stands for the fact that these external events (E^s_{t-1}) and behaviors (B^s_{t-1}) in the past were of sufficient salience to be stored in memory.

We note that in a complete sequential modeling effort, some elements in the set of external events E_t will be from inside the organism, i.e. parts of the nervous system presently not modeled, and could as such draw on the memories, especially the stimulus-reinforcement and the declarative memories, in producing new stimuli. Thereby utility experienced just a few moments ago could indirectly become the input for new stimuli which confirms that emotions, as the expression of utility, can be both consequences of and input to behavior.

3.2 Brief appraisal of the ‘economic view’

The above is clearly a stylized model of the neural processes that lead to an individual’s decisions about behavior. By using insights from the neural sciences it is, however, closer to reality than other theoretical approaches in economics. The model asserts that the brain arrives at decisions based on cost-benefit considerations performed by the relevant brain modules, whereby the actions most promising in terms of emotional value (utility) are picked by a mechanism uniquely designed by evolution to take on this role. The decisions subjected to this mechanism include everything: what to pay attention to, what to take in conscious working memory, what to think, where to move to, what to say on more or less important matters, what to write; i.e. in general: what to do as inwardly directed deliberation and as outwardly directed action. The valuations that are brought to bear are the results of past experiences where the quality of these experiences will determine, e.g. the mix of unreflected action on the one hand, and careful deliberation on the other.

[18] While in Eqs. 6 and 7 a functional relationship explaining a deliberative activity $b^d(\ldots)_t$ is differently presented than for a $b_{i,t}$ in the preceding discussion, it is nevertheless like any other $b_{i,t}$ and was also determined by Eq. 4.

The considerations leading to proposed actions are available as mini programs stored in stimulus-reinforcement memory and as such are tantamount to rules that when followed promise a certain reward. In this respect, the model is consistent with the perspectives of behavioral and new institutional economics with their emphasis on the role of rules. While these two branches of economics look at rules at the level of behavior itself and are interested in their substantive content, the model looks at them at the systemic level, i.e. how they get determined. The model may thus provide insights about the mechanism by which rules or institutions get established in an individual's mind, and why it is that in different people such rules may become more or less productive in terms of generating utility.

The model may also provide insights into what it takes to be the rational agent of economics. One of the rational agent's characteristics is that he takes actions to maximize utility using relevant information and 'commonly acceptable logical inference rules'. The availability of these rules and the agent's ability to use them is not questioned. According to the model, however, this cannot be taken for granted. Whether these rules are available depends on inheritance and experience of the individual, and whether they will actually be used depends on how they fare in the competition with other rules that also vie to be selected for action.

The next section will explore what light the model may throw on this and other selected aspects of economic analysis.

4 Using the model for economic analysis

First we look at how the model relates to theoretical and modeling work both in standard and recent developments of economic analysis. Then we outline how it may be used to throw some light on the phenomenon of trust in economic relations. It is in the discussion of the present section that the transition occurs from explanations of brain processes in terms of economic principles to the analysis of behavior of an economic agent in which these explanations are used as inputs.

4.1 The model within the canons of economic theory and modeling

The central piece of the model is Eq. 4, repeated below in generalized form for any behavioral chunk, $b_{i,t}$, $i = 1, \ldots, n$:

$$b_{i,t} = \rho\left[\left(b^c_{1\cdot i,t}, \Delta u^e_{1\cdot i,t}\right), \ldots, \left(b^c_{j\cdot i,t}, \Delta u^e_{j\cdot i,t}\right), \ldots, \left(b^c_{m\cdot i,t}, \Delta u^e_{m\cdot i,t}\right)\right]. \quad (4')$$

This equation determines $b_{i,t}$, the action responding to a stimulus i, as the outcome of a competition between m different potential candidates, each identified by its expected contribution to utility. The $b_{i,t}$ is the basic unit of the analysis.

Beyond being primarily a descriptive model, we may also look at it as a model of a sequence of simultaneous equilibria. At each time t there will be simultaneous determination of the various $b_{i,t}$ in the process of which the various behavioral chunks are selected; consistency is achieved between different parallel behaviors, and resources are allocated to them. We may want to assume that this process is done optimally, but one may also merely require feasibility of the set of behaviors at each time. Further, the parallel behavioral chunks $b_{i,t}$, $i = 1, \ldots, n$ trace out a path of behavior over a sequence of time periods t, $t + 1$, $t + 2$, ... dependent each time on newly arriving or changing stimuli and on the updated set of memories containing the means with which to respond to these stimuli. This and the likely nonlinearities in the functional relationships make the model a complex adaptive system. This, however, should not be an obstacle to make it a part in a larger such systems mimicking whole economies (see Gintis 2007 cited in Gintis 2006).

It is also a model with learning. There are two routes to learning: the route via unreflected reinforcement-learning and the route via deliberation. Reinforcement learning affects the stimulus-reinforcement and procedural memories. The updating of these memories is dependent on current experience. Deliberation, in contrast to reinforcement-learning, leads to plans and decisions that are concrete entities being stored in declarative memory. For them to become effective they must be transformed into stimuli for the organism to respond to. Note that the first route to learning is normally a byproduct of everyday activities, an unreflected learning-by-doing, while the second route is an activity engaged in with the express purpose of coming up with a new or better result. (We observed earlier that little is as yet known how the brain actually accomplishes this.) Another way of seeing the difference is that when it is implicitly done, learning is not the objective of the relevant $b_{i,t}$ but the brain's relevant systems learn from the activity and store the lessons unnoticed; while when explicitly done as an express activity learning is the objective of the $b_{i,t}$ leading to a concrete piece of output that the brain then 'knows' about and uses, either by storing it or producing a stimulus for immediate action. The two routes in some sense merge, if deliberation leads to plans to do repetitions of certain activities with the objective that the repetitions may increase certain capabilities (grooming a golf shot, sharpening one's arithmetic; see Eq. 7 above). Obviously, there is similarity between the first route and Arrow-type learning-by-doing in business organizations and between the second route and the acquisition of new knowledge based on R&D.

In this model, each activity is intended to produce positive changes in utility, even if it consists of work. (If it turned out that a change in utility caused by an action is negative, this could, according to the model, only have happened because of some error in the decision process, for example, if the basal ganglia is prevented from functioning properly; in Table 1 above we noted one example from real life experiences.) Negative changes should be expected to come about only through external stimuli to which the organism responds in order to eliminate or at least alleviate the negative impact. To see the internal consistency, note that we are looking only at those structures of the brain that are engaged in actually deciding with what actions to respond to stimuli. These stimuli may reach the deciding brain from outside but also from inside the organism, i.e. other parts of the organism than those engaged in this decision process. So when the stimulus of the perceived need for money elicits the response of work, this response will have a positive impact on utility; a subsequent stimulus from inside the organism may then indicate the irksomeness of work which has a negative impact. This may in turn lead to various possible responses: offer a more limited amount of work than originally planned, shirking, efforts to reduce the nuisance of work; all of which in turn would provoke further stimuli to which responses must be found. One point of interest is that the stimulus provoked by actually working may not be one of nuisance but pleasure so that this would even further increase the utility. (Think of a professional athlete who derives great pleasure from doing his job, moment for moment, and not only because of the money.) At this level of generality, nothing in the model would predict that among the alternative activities open to the individual, doing work should necessarily be a disagreeable activity. From this follows that when looking for optimal behavior it may not be so much the search for a *maximum* of utility, where at some point the disutility of the extra work would let the $\Delta u^e_{j \cdot i,t}$ become negative, but of hitting onto a path among several, all of which may promise continuous improvements in wellbeing but at different rates of ascent. For this, presumably, the proper mix of deliberative and stimulus-response activities is one of the necessary determinants. Although the model still lacks the structural and empirical content to do comparable modeling, this perspective is close to that of endogenous growth theory in which the endogenous mix of research (deliberation) and production (stimulus-response activities) are the determinant ingredients (see Solow 2000, chapters 9 and 11).

This brings us to the question of how optimal behavior could come about, and how it could be identified. The model does not allow for one central normative point of view from which it would be clear which behavior leads to the highest change in utility. Instead, optimal solutions would have to emerge as the consequence of the selection—via the basal ganglia, and as expressed in Eq. 4—of successful responses to given stimuli.[19] When these responses are based on the pure stimulus-response rationale they would lead to optimal solutions if reinforcement learning had in the past always picked up the 'right' lessons. This would normally be a slow and, as far as the individual is concerned, not necessarily unfailing route to optimal behavior.[20] There is, however, also the second route to learning whereby knowledge obtained through deliberation is transformed into rules that are better than existing ones. Provided the new rules have sufficient emotional value to overcome older competing rules and are sufficiently often successful in the competition for action, they could be the basis for leapfrogging the slow process of unreflected reinforcement learning. A substantial amount of research in artificial intelligence attempts to model such processes (see Anderson et al. 2004). From an economics point of view, the aspect of competition among rules is of interest, in particular considering that with the one or other type of rules being more or less predominant, people with quite different capabilities to select optimal solutions would be expected to emerge over time. This leads straight to the question what this implies for the concept of the representative agent. Does it strengthen the argument advanced by Kirman (1992) to abandon the concept in favor of that of the heterogeneous agent?

As indicated earlier, the model serves to sharpen an understanding of rationality as used in economics. To the notions that utility is maximized and inferences are made

[19] In this, the model is also similar to growth theoretical models in which, if one does not presupposes a central planner, one has to search for conditions that would guide the economy on the optimal growth path.

[20] For a demonstration of this point see Erev and Roth (1998) who find that a variable for reinforcement learning is astonishingly successful in explaining results of experimental games that when played over many rounds only slowly or not at all converge to the equilibrium values.

on the basis of logical rules, Elster (1997, p. 761) adds the following characterization which he attributes to Becker (1996): '(T)he concept of rationality is subjective through and through. To be rational does not mean that one is invariably successful in realizing one's aims: it means only that one has no reason to think that one should have acted differently, given what one knew (and could have known) at the time. Nor does a rational belief have to be true: it must only be well-grounded in the available information. Nor, finally, should the rationality of a life plan be assessed after the fact or by an external observer: it must be assessed by the agent before the fact.' Given this characterization as well as the model's specification of how the decisions are arrived at, one first needs to determine *by what* the individual is represented that 'knew (and could have known)' or the beliefs of which 'must be well-grounded in the available information.' It should be the brain processes that generate the answers to the queries implied in the quote from Elster. The candidates would appear to be the brain processes that generate focused deliberative actions. These brain processes may be diffusedly localized throughout the brain but manifest themselves as the rational individual each time they are able to decide on an action. The alternative would be the ensemble of all brain processes, also those that follow stimulus-response actions. But this would render Elster's description vacuous as no action could ever be irrational. Also, remember example (iii) of Table 1 where on a question whether to undertake an investment now or postpone it, the decision maker may give in to urgings for a quick decision, although to postpone it would have been his preferred action. This indicates conflict between two sides of the brain within the individual of which only one would here be the rational side. From the perspective of the model, a high degree of rationality would obtain through a balanced mix of deliberative and stimulus-response actions—the one or other type being given preference depending on circumstances—which by experience assures greatest positive utility changes over time and which minimizes occasions of errors and consequent detrimental behavior, given that the latter cannot completely be avoided. This conception of rationality also makes the relevance of Elster's before-the-act-rationality doubtful. It would allow that the rationality of an act is questioned after the fact, by the individual himself and also by an external observer, since by construction there is always the possibility that, although the individual knew the relevant facts, he nevertheless acted wrongly due to the predominance of a contrary candidate response.

It appears that the model would easily fit with a number of recent developments in economics. At the conceptual end, it could most readily be linked with the approach of Kahneman (see for a review his Nobel lecture 2003). His two systems 'Intuition' (system 1) and 'Reasoning' (system 2)[21] are largely consistent with the two ways of arriving at decisions modeled here. Processes of system 2 would, in the model, be the deliberative activity and those of system 1 be all the stimulus-response determined actions. What the model adds is a mechanism that determines how either of the two systems is activated, and it shows that this mechanism is actually, as it were, a system 1 mechanism that in the end also decides whether system 2 activities will take place. At the applied end, the model's insights could contribute to computational, heterogeneous

[21] In Kahneman's scheme there is also a separate role for perception which, as will be remembered from the discussion above, is in our model subsumed within the stimulus-reinforcement mechanism.

agent-based economics as discussed in Tesfatsion (2006). The requirement would be that the processes determining an agent's behavior are operationalized, either on the basis of empirical observations or on the basis of an a priori but internally consistent specification. This would allow us to study the implications of agents that, according to different experiences and inclinations that they are endowed with as initial conditions, follow and develop different strategies by using their skills, in particular their capacities for rational action, to cope with the problems they are faced with.

4.2 How the model could enrich the analysis of trust

Trust or trusting behavior is part of a large domain of economic interactions. It has, however, a spotty record in economic analysis. Williamson (1985) did not find the concept useful as everything that looked like trust would in the end turn out to be the result of some self-interested calculation. An early example of analyzing trust as an important phenomenon in its own right is Landa's (1981) law-and-economics analysis of a trader's choice of trading partners in an environment where contract law is not well-developed. A rational trader will have the incentive to choose trading partners whom he can trust; they are often kinsmen and people from the same ethnic group who share the same norms. The result is the emergence of the 'ethnically homogeneous middleman group' (EHMG), a club-like trading network, which serves as an institutional alternative to contract law. It is the mutual trust between trading partners in close social proximity/social distance that enable traders to develop the EHMG which facilitates the enforcement of contracts. Subsequently, Denzau and North (1994) picking up this topic, pointed out that at the basis of institutions there lie shared mental models and shared values which, in turn, allow mutual trust to develop especially among groups that are already homogeneous along some dimension.[22] Trust has also become one of the major themes in experimental economics spearheaded by Vernon Smith (see his Nobel lecture 2003). Smith and others have shown that in the so-called trust games with two players[23] a substantial proportion of the players in fact behave trustingly or respond in a trustworthy manner. Given that these games are often one-shot games and carried out under conditions of anonymity, it is hard to argue that the revealed trusting and trustworthy behaviors should be based on enlightened self-interest. Researchers in neuroeconomics have been probing into what the neural substrates for trusting behavior might be. Zak and collaborators in a series of studies have identified the hormone oxytocin which, active in various structures of the brain primarily through the release of dopamine, would affect the degree of trust exhibited by the tested persons (see Kosfeld et al. 2005; Zak 2007). For Zak, these findings are an important step toward an understanding of the mechanisms that produce cooperative behaviors.

[22] Denzau and North, however, did not cite Landa's work but cited LaCroix (1989) who discusses and elaborates on Landa's theory of the EHMG.

[23] In trust games with two players, the first player may make a move the success of which depends on the trustworthiness of the second player, and this one may respond by rewarding the trust placed in him so that both are better off than in the case if the first player had not trusted the second player. There is a large literature on trust games. A pioneering work is Berg et al. (1995).

Following the model of this paper, any behavior involving trust would be a response to stimuli perceived by the agent where that response would: (a) be expected to generate a value higher than other potential responses competing with it; and (b) could be of two kinds: outwardly directed behavior, such as assenting to a deal in which the outcome will depend on the trustworthiness of the other side, or inwardly directed, such as deliberating about the advantages or disadvantages of trusting behavior.

At the one extreme, the first kind of behavior may consist of the stimulus-response variety where the person engages unreflectedly in the trusting act. The 'rationale' for this behavior would be that similarly unreflected trusting behavior has in the past proved to be to the benefit of the individual, so that due to the effects of reinforcement-learning the individual has a strong tendency to exhibit this trusting behavior in all similar situations. It may, however, also be genetically programmed; the relationship between infant and mother would be typical in this regard. According to this reading, the differing levels of oxytocin would be the route by which the chemical machinery of the brain values the various stimuli. This type of behavior would not involve any overtly self-interested calculation that Williamson is suspecting.

The second kind of behavior is based on the ability of humans to explicitly reflect on situations, in particular also on their own actions. An individual may perceive that persons engage in unreflected trusting behavior—this perception being the stimulus that the individual reacts to—and that such behavior seems to be beneficial in given situations, and she may start ruminating about what this may imply for herself. Thus, at the other extreme, there may be a person with no inclination toward unreflected trusting behavior but whose deliberations may usher into a plan to act trustingly in the future on certain occasions. Whether the plan becomes reality would then depend on the prescriptions for behavior derived from this plan being able to overcome competing responses to the relevant stimuli. This would then be the Williamson 'calculative' type of trust. Over time such behavior may become an unreflected response like the first type, the difference remaining, however, that it was learned following an explicit deliberation, while the first type was acquired unreflectedly.

As an example of how the model may add to one of the approaches outlined above, consider Landa (1981). She discusses how a member of a Chinese EHMG may have decided with whom to deal on the basis of credit or on the basis of cash . He would carry out a 'calculus of relations' (Fortes 1969) in which potential trading partners are classified in terms of the degree of social distance as near kinsmen, distant kinsmen, clansmen and extending outwards to Europeans and indigenous peoples, and drawing the boundary line between 'insiders' and 'outsiders'. The present model would suggest that in the concrete historical setting, all sorts of trusting behavior initially existed between socially close individuals occurring on an unreflected basis. When this trust made it possible to trade on a credit basis, this then proved to have beneficial consequences which could be enhanced if such a trust was extended to members of groups at a somewhat greater but still relatively close social distance. When an EHMG network arose out of these personalized transactions based on reinforcement-learning, and members became aware of the EHMG itself and its benefits, they also noted the incentives to enlarge and at the same time optimally circumscribe it. At this moment, network members would be confronted with the stimulus to develop, individually or as a group, the explicit 'calculus of relations' (Fortes 1969) as discussed by Landa.

The noteworthy point is that out of many relationships of trust among a socially close group on an unreflected basis, a 'larger' relationship could be developed to generate a greater benefit but this opportunity had to be recognized and deliberately dealt with to be able to fully exploit it.

Zak (2007) hypothesizes that trusting behavior, irrespective of its merits in terms of outcome, may for some individuals be in itself rewarding, perhaps due to a genetically caused relatively high level of oxytocin. From this follows that such behavior might persist even if being trusting were not worth the benefit. One question then concerns the impact on society at large when there are many more trustworthy individuals of this sort, trusting more than would objectively be reasonable. One would expect an externality effect on those that are not subject to the oxytocininduced trusting behavior where it is a priori not obvious whether the effect would be beneficial or detrimental. There would obviously be the risk of exploitation by those who become aware that people have this inclination. The question would arise whether too much trusting could be a stable behavioral trait, or under what conditions individuals affected by it may become aware of this relationship and take deliberate measures of adjustment.

The role of oxytocin needs clarification in general. Is its level in the bloodstream determined exogenously and would it therefore contribute to trusting behavior in a correspondingly fixed amount? Or does it only serve as a transmission belt that implements trusting behavior that is ultimately determined by some other factor so that the level of this neurochemical is actually an endogenous variable? A possible hypothesis may actually be that all brain activities are modulated neurochemically and that there are genetically determined *basic* levels of the neurochemicals in question but *overall* levels vary due to learning in reaction to events in the environment.[24] It should then be an interesting research question what the concrete links are between learning and the implementation of its results through the relevant neurochemical channels.

The model offers a common framework within which to consider determinants of trusting behavior—and for that matter other economic behavior as well—and is thereby able to integrate the different research findings reported above. This ability to incorporate findings from quite different styles of research is due the methodology of operating on two levels of analysis. At the level of brain structures it integrates the observations reported by the research group around Zak, and at the level of a person it is able to throw light on observed behavior by explaining it in terms of the processes of these brain structures.

5 Summary and concluding observations

Neuroeconomics draws attention to motive forces that are ignored in the standard framework of economic theory. The present paper develops a conceptual approach that, similar to Pennings et al. (2005), tackles the issues at the systemic level by ana-

[24] Experiments have apparently so far been restricted to tests of the effect of artificially induced changes in the level of oxytocin on the test persons' degree of trusting behavior (see for example Kosfeld et al. 2005). There seems to have been no test of the hypothesis that the level of oxytocin changes as a consequence of some other mechanism and that these changes in oxytoicn just serve as a transmission belt for changing trusting behavior.

lyzing and modeling the brain processes that decide on behavior. It takes as the basic unit of analysis potential stimulus-response actions which—when selected—become actual behavior. These potential stimulus-response actions all aim at increasing utility. At any moment of time several of these potential actions compete with each other for the privilege of becoming actual behavior. This competition can be modeled on the basis of economic principles. The behavior that materializes may cover the range from the rational to the foolish depending on which of the potential responses gathers the greatest emotional strength. The emotional strength of a potential response, in turn, is determined by the individual's past experience and her capacity for rational action. Given that the objective is always to increase utility, it can normally be expected that the more or less rational dominates the foolish, but this need not always be the case. Which potential actions become actual behavior is decided by the basal ganglia, a structure in the brain serving as the action selection mechanism. The insights provided by this approach afford coherent explanations of behaviors that are not readily explicable by the standard approach.

The approach may be seen as a step towards providing the tools needed to model an individual's economic behavior whenever that behavior is thought to involve more than maximizing a utility function based on given preferences. One aspect of behavior found to be important is the degree of deliberation used in agents' decision making. A promising application might be the modeling of agents that are able to use deliberation in their decision making in varying degrees, and have these agents populate models of whole economies. A prerequisite would be that the relevant trade-offs in terms of costs and expected benefits of using deliberation instead of immediate unreflected action (the criteria of substitution) are specified, which is a task that would still need to accomplished.

The model still needs to be concretely specified and to be refined and extended. It would be ideal if such efforts could be informed by further results of neuroscience research. Conversely, since the model is grounded in empirical observations from the neurosciences, the insights derived from it may yield hypotheses providing clues for this research.

Acknowledgements I thank the editor, Janet Landa, and an anonymous referee for criticisms and comments which greatly helped to make this a better paper. Any remaining errors and misconception are my responsibility. My interest has been drawn to this subject inter alia through work as a regulatory economist at WIK, in particular by the difficulties of communicating to the public the implications of regulatory reform of the telecommunications sector, respectively, the emotional resistance in some quarters to such reform.

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