SCIENCE AND SOCIETY

Translating upwards: linking the neural and social sciences via neuroeconomics

Clement Levallois, John A. Clithero, Paul Wouters, Ale Smidts and Scott A. Huettel

Abstract | The social and neural sciences share a common interest in understanding the mechanisms that underlie human behaviour. However, interactions between neuroscience and social science disciplines remain strikingly narrow and tenuous. We illustrate the scope and challenges for such interactions using the paradigmatic example of neuroeconomics. Using quantitative analyses of both its scientific literature and the social networks in its intellectual community, we show that neuroeconomics now reflects a true disciplinary integration, such that research topics and scientific communities with interdisciplinary span exert greater influence on the field. However, our analyses also reveal key structural and intellectual challenges in balancing the goals of neuroscience with those of the social sciences. To address these challenges, we offer a set of prescriptive recommendations for directing future research in neuroeconomics.

Neuroscience has been remarkably successful in elucidating the mechanisms that underlie human and animal behaviour. This success has led to an explosion of interest in translational research in which mechanisms identified through basic science are brought into direct clinical practice through connections between systems neurobiology[1] and mental health[2]. Translations of neuroscience research from the laboratory to the wider society have been historically much less frequent. However, in the past decade, new scientific fields have arisen that apply neuroscience to core questions in the social sciences and humanities, including neuromarketing[3], neuropolicy[4], neuroethics[5], neuroesthetics[6] and neuroeconomics[7–12]. In this Perspective, we evaluate one of these attempts, neuroeconomics, and its implications for guiding the integration of the neural and social sciences.

Neuroeconomics comprises research on the biological mechanisms of decision making[13,14]. It combines concepts from neuroscience, genetics, economics and psychology, and seeks to identify general mechanisms, from the response of single neurons to the large-scale behaviour of markets[15]. Early manifestos argued that the goal of neuroeconomics was to draw a biologically sound conception of rationality and individual choice, two concepts at the core of economic sciences[16,17]. Indeed, any shift towards a more biological foundation would reflect a radical turn for economics, as physics, rather than biology, has been the natural science with the most influence on economics throughout most of the past century[18,19]. Conversely, by introducing many of the core methodological principles and models from economics (potentially via the intermediary of psychology) to neuroscience, neuroeconomic research could lead to new interpretations for the mechanisms of decision making studied by neuroscience[14].

Here, we consider how neuroscience data have influenced and should influence economics, both through effects on research communities and by effects on disciplinary practices. First, we consider whether neuroeconomics has grown into an integrated community. Social network analyses[20] allow quantitative assessment of whether its collaborations and publications span the neural and social sciences or whether they instead reflect juxtapositions without true disciplinary coherence. Second, we examine, on the basis of a textual analysis, whether these collaborations stimulate the creation of interdisciplinary topics and concepts and, if so, how this research fits into the broader relationships between economics and biology. We conclude with suggested steps for reducing discordance and increasing links between the neural and social sciences.

An integrated community?

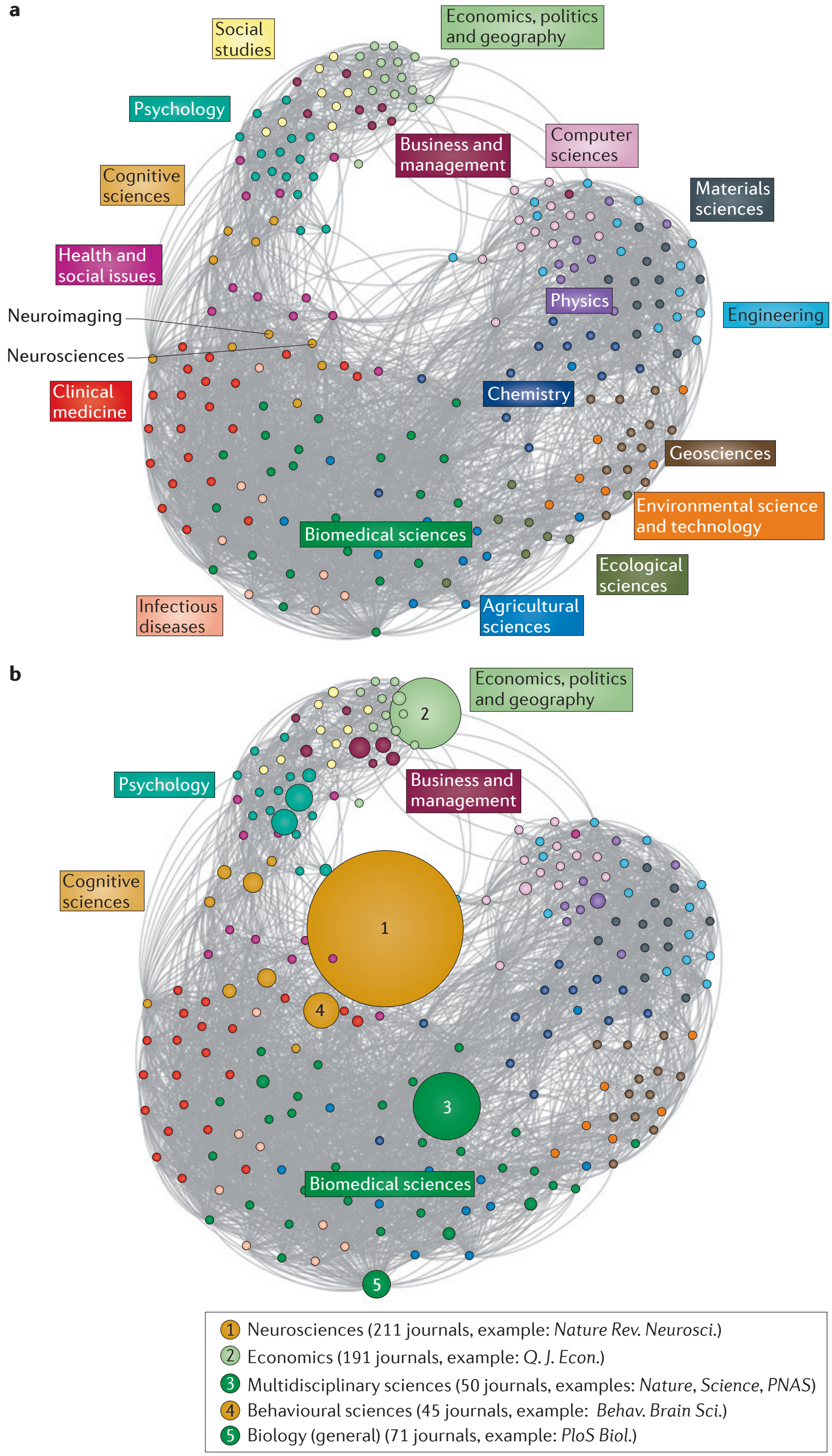
Neuroeconomics draws intellectual inspiration from several subdisciplines of neuroscience (such as systems neuroscience and cognitive neuroscience) and from multiple fields within the social sciences (including behavioural economics, social psychology and decision theory). Accordingly, its practitioners exhibit a remarkable diversity in how they form research groups and report results. Such diversity could either catalyse progress at the margins of disciplines or pose a barrier for effective communication between researchers depending on whether researchers tend to collaborate (and publish) across traditional disciplines. To quantitatively evaluate the intellectual connections within the neuroeconomics field, we used scientometric and online survey data to describe how projects develop and scholars interact.

An elegant way to quantify and map interactions between scientific disciplines is to use recent graphical innovations in scientometrics[21–23]. Following conventions in the field (see REF. 24 for example), scientific disciplines can be organized on the basis of the patterns of citations in scientific journals (see Supplementary information S1 (box) for methods). Groupings of scientific journals into disciplinary categories (as defined by the scientific information provider Thomson Reuters Web of Knowledge) can be represented as nodes in a network (FIG. 1). For instance, *Nature Reviews Neuroscience*, the *Journal of Neuroscience* and 209 other journals are grouped in the 'neurosciences' subject category. The strength of a link between two nodes depends on their shared bibliographical references. As an example, the subject categories 'neurosciences' and 'neuroimaging' are strongly connected, as the papers published in journals in these disciplines frequently cite the same bibliographical sources. The resulting map — the spatial layout of which minimizes the distance between related nodes — reveals a clear structure: social sciences are strongly connected to psychology, which in turn is close to cognitive science and the biomedical sciences. The physical and material sciences are at the other end of the spectrum and connect with the biomedical sciences via chemistry[24] (FIG. 1a).

The positioning of neuroeconomics on this map can be viewed by scaling the size of each node according to the number of neuroeconomics papers published in the corresponding subject category (FIG. 1b). The resulting scientific landscape exhibits a range of disparate peaks. Here, neuroeconomics spans three main disciplinary domains — 'cognitive sciences', 'economics' and 'biomedical sciences' — and has a substantial presence in two others ('psychology' and 'business and management'). This diversity of coverage is exceptional, as even interdisciplinary fields usually publish predominantly in a restricted geographic region within these scientific maps (see Supplementary information S2 (box) and S3 (figure) for a comparison with two other interdisciplinary fields: evolutionary economics, and social and affective neuroscience)[25]. By itself, the map provides evidence that neuroeconomics research has permeated a range of scientific disciplines, which provides favourable conditions for the evolution of an interdisciplinary community.

But does interdisciplinary publication necessitate an interdisciplinary community? To address this second question, we used network analyses based on a survey of 820 individuals to characterize the social connections between neuroeconomists from different academic backgrounds (BOX 1).

Our survey indicated that many researchers in neuroeconomics have developed connections to scholars from disciplines other than their own. These collaborations with a range of social scientists — not only psychologists — are a relatively new feature within neuroscience, as many of them are only a few years old. Importantly, diversity within research groups is greatest for groups positioned near the centre of the network of communications (FIG. 2). This result can also be appreciated on the visual display of the network of communications (BOX 1), in which communities of researchers with a balanced disciplinary composition occupy a central position. This suggests that intellectually



diverse groups are engaged in more partnerships and reach a wider audience, possibly leading to more influential research.

Thus, over the past decade, neuroeconomics has developed into an integrated research community that spans a number of traditional disciplines. However, as the size of the field has grown, the relative usage of the term 'neuroeconomics' is decreasing in favour of the term 'decision neuroscience'

◀ Figure 1 | **The disciplinary connectivity of neuroeconomics research.** Relationships between scientific disciplines are depicted in a network based on patterns of citations in scientific journals (Supplementary information S1 (box)). **a** | Each node represents one subject category (categories as defined by the scientific information provider Thomson Reuters Web of Knowledge), and related subject categories are grouped into broader scientific disciplines (each shown in a different colour). For example, the discipline 'cognitive sciences' (shown in brown) contains, among others, the subject categories 'neurosciences' and 'neuroimaging'. Two subject categories are linked if their journals make frequent references to the same bibliographical sources. For instance, the subject categories 'neurosciences' and 'neuroimaging' are connected, as the papers published in their journals frequently cite the same bibliographical sources. The topology of the map shows the overall organization of scientific publication as a curved surface, such that broad scientific fields (such as 'infectious diseases' and 'engineering', which are shown in light red and light blue, respectively) form an axis that ranges from 'economics, politics and geography' (upper left) to 'physics' and 'materials sciences' (upper right). **b** | We rescaled each node (that is, each subject category) shown in part **a** according to the number of neuro-economics articles published in the journals within that subject category (see Supplementary information S1 (box)). The smallest circles reflect 0 publications in neuroeconomics. Although most scientific disciplines comprise publications in a small number of neighbouring subject categories[25] (see Supplementary information S2 (box) and S3 (figure) for a comparison of neuroeconomics with two other interdisciplinary fields), this map shows that neuroeconomics articles are published in a large number of journals with a relatively heterogeneous set of subject categories both from life and social sciences (data are from REF. 24).

(FIG. 3 and Supplementary information S4 (figure)). What could have caused this shift? One possibility is that there has been asymmetric influence across the disciplines; for example, paradigms from economics may inform neuroscience research, but data collected in neuroscience may have little direct relevance for research in economics and the other social sciences[26,27]. Translating behavioural findings downwards to shape basic biological inquiry may be more practical than translating basic science findings upwards to complex societal issues. Thus, successful translations downwards ('decision neuroscience') may simply be more frequent than successful translations upwards into the social sciences ('neuroeconomics'). In the following section, we consider what sorts of inferences both the neural and social sciences draw from neuroeconomics research.

An integrated literature?

The analyses in the previous section indicate that neuroeconomics has come together as an integrated research community, one that draws scholars from the breadth of the social and natural sciences. But does its research output reflect a similar integration of these various disciplines? Or do concepts from particular disciplines dominate the existing literature?

Mapping concepts in neuroeconomics. To obtain a quantitative picture of the state of the neuroeconomics literature, we applied semantic network analytic methods to a comprehensive corpus of scientific articles in the discipline. From an initial set of 27 review articles surveying the neuroeconomics literature (Supplementary information S5 (box) and S6 (table)), we extracted every article that was cited in at least two of those reviews, leading to 259 unique references. (Of note, the distribution of citations was highly skewed, such that only 15 articles were cited in more than one-third of those reviews.) We used natural language processing techniques to extract frequently mentioned concept terms from the abstracts of those 259 references. The degree of connectivity between two concepts was calculated on the basis of the number of co-occurrences of those terms within individual abstracts. We created a semantic map that illustrates the intrinsic structure of the neuroeconomics literature based on the conventions that more frequently occurring terms are represented in larger size and connected terms are depicted closely together (FIG. 4).

Several features of this concept map are apparent. First, there is considerable intermixing of terms with origins that lie in different disciplines. For example, the bottom portion of the graph (green) contains intercalated concepts from neuroscience (for example, striatum or dopaminergic), economics (for example, expected value or incentive) and psychology (for example, motivational). Thus, there is substantial local heterogeneity within the neuroeconomics literature, mirroring the heterogeneity of research groups at central positions in the network of neuroeconomists. Second, there are several large clusters that correspond to major topics of research. One cluster (right middle and bottom) comprises terms associated with reward evaluation and the brain's dopamine system, reflecting a clear example of the integration of behavioural modelling and neuroscience data[28,29]. Two other clusters broadly contain terms associated with strategic decision processes (left top, for example, cooperation and game) and terms associated with emotional and affective processes (left middle, for example, arousal and insula), respectively. Third, there is a notable method-based grouping, such that terms associated with primate electrophysiology tend to cluster with measures of behaviour (for example, eye movement) and neural targets for recording (for example, dorsolateral prefrontal cortex). Last, there is an intriguing large-scale structure that suggests a progression from basic neurobiological notions at the bottom right (for example, caudate and ventral striatum) to more complex economic and psychological concepts at the upper left (for example, fairness and economic decision). This 'brain-to-function axis' indicates that despite the local heterogeneity mentioned previously, the neuroeconomics literature evinces stronger connections between concepts originating in the same discipline than between concepts that cross disciplines.

Has neuroscience influenced economics? Economists and biologists have a history of dialogue and exchange dating at least from Darwin's borrowing of the principle of population growth from Malthus[30]. In return, Darwinian evolutionary theory and population genetics have had a pervasive influence on the theorizing of the behaviour of the firm and the dynamics of economic systems[19]. The contacts between economics and neuroscience are relatively more recent and their influence on the general economic literature less clear.
We examined the content of all abstracts published over a recent 10-year period in 57 economics journals of general interest (see Supplementary information S7 (box), S8 (box) and S9 (figure)). A total of 222 articles considered concepts from neuroscience, genetics or other biological sciences. Analysis of the content of their abstracts revealed a striking disconnect with the neuroeconomics literature; although the 222 articles considered topics such as 'the genetic basis' of family- or health-related phenomena (for example, genetic, twin, birth weight, intergenerational and so on) or the evolutionary character of strategic behaviour (for example, evolutionarily stable, adaptive, game and so on), few articles discussed neuroscience (see Supplementary information S9 (figure)). Even in those economics articles that included terms from neuroscience (for example, dopamine, ventral, neural and so on), these terms were tightly grouped in a cluster, despite their demonstrated relevance in a range of other topics (such as

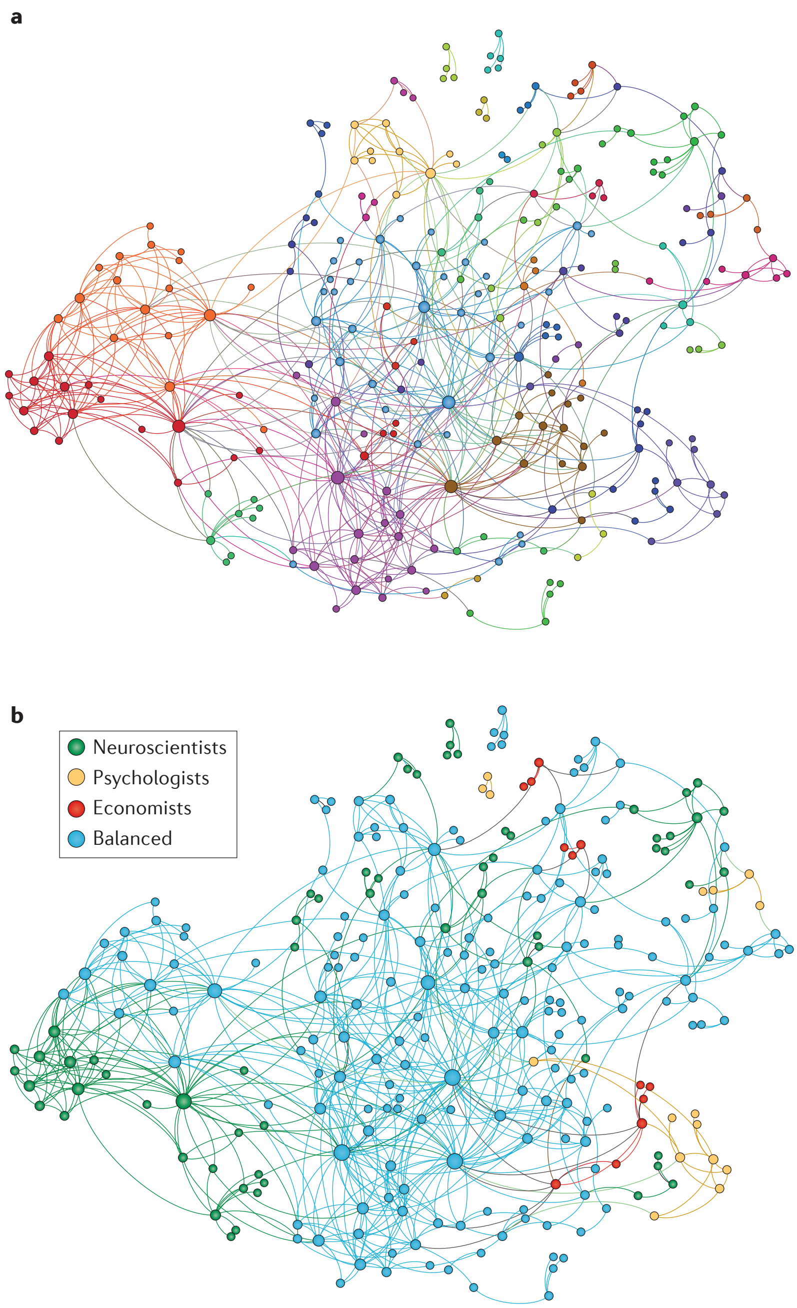
game-theoretic approaches to behaviour[31,32]). In short, there is little evidence yet that neuroscience research — apart from review or opinion pieces — has penetrated the mainstream economics literature.

Does this discordance between the neuroeconomics and economics literatures reflect a fundamental incompatibility between the two fields? Some differences between these literatures do reflect disparate intellectual goals. The economics literature often evaluates the consequences of decisions made in real-world contexts and over long time horizons, such as in the case of research on the effects of socioeconomic status on decisions about health care or in labour markets[33]. Experimental analysis of such factors is beyond the current scope of neuroeconomics, which typically explores decisions in controlled laboratory settings and about small-scale personal rewards[34]. However, other topics are central to both disciplines, such as risk preferences, temporal discounting, social interactions and strategic choice. Indeed, the economics literature has considered these topics within both experimental and theoretical research, linking them to concepts drawn from evolution and sociobiology[35,36]. Thus, the cardinal challenge for neuroeconomics is not to convince economists (and other social scientists) that biological findings can be relevant for their work, but to demonstrate that neuroscience can make unique and distinctive contributions to the understanding of economic behaviour[14,15]. In the following section, we recommend specific steps towards this goal.

Box 1 | **Social networks in neuroeconomics**

Social network analysis provides a framework for the identification and assessment of formal and informal interpersonal networks. Although network analysis has been used before to study social groups within science[93–95], a direct survey of the social network of an entire field has not been attempted before. We contacted, via e-mail, all scientists who had co-authored at least one publication mentioning 'neuroeconomics' in the title, abstract or keywords (Supplementary information S10 (box)). Within this survey, we asked participants for the names of colleagues with whom they discussed their research in neuroeconomics. This question provided a total of 820 unique names; for each, current organizations, research activities and training discipline were identified via manual Internet searches. For the resulting subset of 313 individuals who expressed neuroeconomics among their interests, the interconnections were mapped and quantitatively evaluated (see the figure, part **a**, which shows the pairwise connections between scientists — each scientist is shown as a single node whose size reflects the number of connecting links). Of note, the resulting community is very cohesive, with one connected component comprising 82% of the neuroeconomists and 98% of the interconnections in the network. This means that despite geographical distance and differences in academic affiliations, neuroeconomists interact through an inclusive and disciplinarily diverse conversation network.

However, large-scale heterogeneity could mask small-scale homogeneity if individual neuroeconomic research groups are biased towards one disciplinary background or another. Using an algorithm for non-supervised community detection in networks[96], we found 47 distinct communities in the network of neuroeconomists (groups are shown by arbitrary colours in the figure, part **a**). Not surprisingly, these communities tend to correspond to key laboratories or centres at major institutions. For each community, we assessed whether its disciplinary composition is balanced, in the sense that no one discipline provides a majority of its members. Some communities primarily consist of individuals from the neural sciences (including non-neuroscience biologists), from economics or from psychology (see the figure, part **b**, in which these are shown in green, red and yellow, respectively), but a large proportion (62%) of the 47 communities have a balanced composition between the three disciplines (shown in turquoise in the figure, part **b**). Moreover, balanced communities tend to occupy more central positions in the network, as can be observed visually (see the figure, part **b**) and evaluated statistically with centrality measures (FIG. 2 and Supplementary information S11 (box)).



Connecting the neural and social sciences
Neuroeconomics has overcome some of the challenges that are typical to interdisciplinary research — such as how to develop interdisciplinary courses, how to withstand waves of scepticism and how to create a social group of scientists with varied disciplinary backgrounds — to function as a burgeoning interface between neuroscience and economics. Interdisciplinary neuroeconomics communities can now serve as fertile ground for training students at the boundaries of disciplines. Indeed, although extensive training programmes are still in development, some researchers now work as neuroscientists in business schools or as economists within cognitive neuroscience groups. The hope is that these individuals operate as channels for communication between disciplines, both within their institution and in the larger fields.

However, some obstacles continue to hamper connections between neuroscience and economics. For example, the research cultures of neuroscience and economics can seem foreign and inscrutable from the other's perspective. Neuroscientists are incentivized to work in large collaborative teams, to continually seek extramural funding and to prioritize research directions that rapidly lead to high-impact work, whereas economists operate within a different model for research, funding and mentorship. Economics journals operate on a different timescale (for example, articles and review cycles are longer), collaborations are usually on a smaller scale (for example, fewer co-authors on articles) and research directions may be disconnected from the goals of funding agencies. Given the size and history of both disciplines, neuroeconomics is unlikely to completely overcome these differences.

How then should future research in neuroeconomics go about building connections to economics and other social sciences? On the basis of the results from our analyses in the previous sections — including the evidence that neuroeconomics has been effective at growing local interdisciplinary communities — we argue that neuroeconomics can be a dedicated communication channel between disciplines. By allowing researchers to trade concepts across disciplines and develop new hypotheses within disciplines, neuroeconomics can improve the match between the demand for biological concepts in economics and what economic models can offer to neuroscience. Below, we indicate four approaches by which neuroeconomics can improve communication between neuroscience and economics.

Targeting general neural mechanisms. Neuroscience investigations of how the brain computes preferences and makes choices ultimately aim to identify the fundamental neural mechanisms underlying these processes. From the perspective of the social sciences, economics stands in a similar position. From small sets of axioms, it creates models of multiple facets of decision making — from analyses of investment decisions to studies in consumer preferences — that share fundamental economic principles. Unfortunately, the fundamental elements that are identified separately by neuroscience and economics are not easily comparable[27], making it difficult for the two disciplines to adopt common hypotheses. Here, neuroeconomics can develop the conceptual interface needed to help neuroscience and economics identify general principles of behaviour.

Substantial progress has been made in this direction with the detailed description of the neural circuits involved in value-based choice[15,37,38]. With a fully fledged correspondence between economic and neurobiological descriptions of decision making, each discipline could in principle appeal to the results obtained in the other. Economists would be able to prune their models based on the neuroscientific plausibility of their underlying hypotheses. (For example, should valuation models systematically include a reference point? Neuroeconomics points in this direction[15].) New hypotheses could be generated, such as testing whether two previously independently studied types of economic behaviour (for example, moral behaviour and consumer spending) are related, considering that the same well-specified neural mechanisms (including cognitive control) are involved in both. (Note that similar proposals have been made for understanding clinical conditions[39].)

Neuroscience would also benefit if its models of decision making could be related to economic models of decision making. Shifting contexts (such as making decisions for oneself versus for a friend) can change the extent to which decision makers rely on particular sorts of neural computations (for example, working memory versus emotion). Accounting for the possibility of such a cognitive shift — via some parameter in a model — can improve the ability to isolate the contributions of particular neural processes to an observed behaviour. In addition to choice context, neuroscience routinely studies conditions that alter basic information processing in the brain (for example, state manipulations). Differences in information processing have been found with

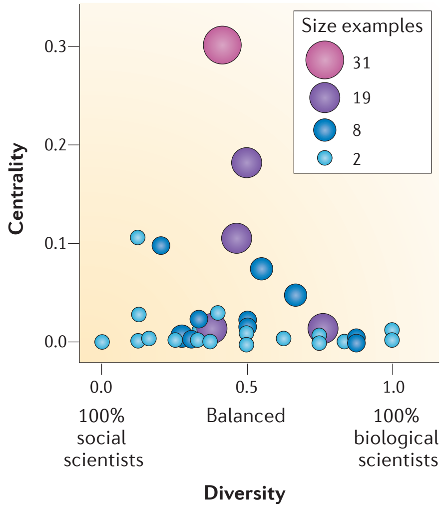


Figure 2 | **Interdisciplinary research groups occupy more central positions in the community of neuroeconomists.** For each cluster in the social network of neuroeconomists (BOX 1), we calculated a diversity index (*x*-axis of graph), with values of 0 representing a cluster with only social scientists, 1 representing a cluster with only biological scientists, and 0.5 representing a completely balanced cluster. We next calculated the betweenness centrality for every cluster in the network; essentially, this provides a measure of the frequency with which indirect connections between any two clusters pass through that cluster (so that clusters lying between many other clusters score highly on this measure). We found that clusters with balanced disciplinary composition (*x*-axis) tend to occupy more central places (*y*-axis) in the discipline.

pharmacological studies[40], manipulations such as sleep deprivation[41], or comparisons of different age groups[42,43]. Identification of a general neural mechanism of decision making requires an understanding of the limits of such adaptive flexibility and a clear specification of the decision process, both of which can be provided by studies in neuroeconomics.

Increasing the focus on individual differences. How individuals make decisions has long been a central question within economics. However, few economic models provide insight into the way in which choices are affected by individual differences in personality, cognitive abilities or other factors, let alone into how such individual differences arise or are distributed throughout a population. Neuroscience, by contrast, provides a wealth of tools for assessing differences among individuals. Differences in brain structure (for example, local grey matter density and white matter tractography) can predict individual differences in cognitive function[44], which in turn may predict real-world behaviour. Moreover, functional responses of the brain have been linked to a host of personality factors[45–47] and to specific choice biases[48]. In addition, genetic differences may explain some of the inter-individual variability in economic preferences[49], as several gene variants that associate with differences in brain structure and function have been identified[44,49]. As shown by these examples, neuroscience research could enable the characterization of lower-level individual differences in neural computations that may be linked to inter-individual variability in economic behaviour.

An increased focus on individual differences in neuroeconomics would also pair well with modelling work in cognitive psychology[50–52]. Consider self-control issues, which have been modelled extensively in both economics[53,54] and neuroscience[55–58]. A demographic factor such as socioeconomic status may influence self-control through a number of pathways. For example, low socioeconomic status has been associated with poor nutrition and increased stress during early life[59], and these conditions are known to impair brain development in childhood[60], which in turn may affect prefrontal cortex function in adulthood[61]. As different parts of the prefrontal cortex contribute to various computations involved in self-control[55,62,63], socioeconomic status may have latent effects on how people express preferences and make decisions. Thus, expansion of decision making models to include factors associated with individual differences in various decision parameters would increase the mutual relevance of neuroscience and economics[26,64,65].

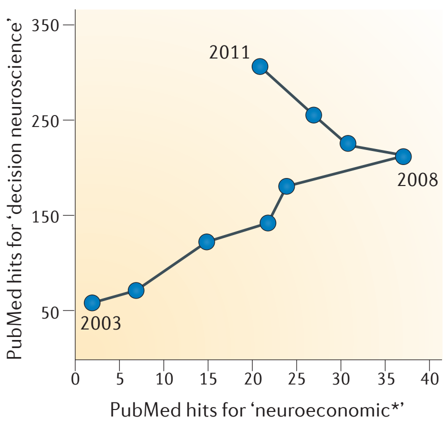


Figure 3 | **Literature usage of 'neuroeconomic*' and 'decision neuroscience'.** We collected the absolute frequency of the terms 'neuroeconomic*' and 'decision neuroscience' in PubMed (retrieved on 20 January 2012), with the goal of assessing its relative usage within the larger scientific literature. We found the first appearance of 'neuroeconomic*' in 2003 (two articles). A year-to-year breakdown demonstrates a constant increase since 2003 in articles referring to 'decision' + 'neuroscience' (arguably reflecting an overall increase in the size of the field), but a recent downward trend of articles using the term 'neuroeconomic*', with a peak in 2008 (37 articles). Note that the combined term 'decision neuroscience' entered the literature in 2009, the first year following the point of inflection on the graph. An analogous search on Thomson Reuters Web of Knowledge yielded a similar trend (see Supplementary information S4 (figure)).

Moving beyond the laboratory. It could be argued that the ultimate test for the usefulness of a research finding is whether it has external validity. Laboratory experiments are now widely accepted in the economics community[66], in part because of links between laboratory results and field measures in economics[67,68]. Could neuroscientific laboratory studies also predict everyday economic behaviours? Neuroeconomics is ideally suited to develop this new form of translational research, if neuroscientists obtain neurophysiological measurements in a controlled environment and economists relate these measures to economic behaviour observed at the population level. Consider the findings in economics that hypothetical time–money discounting survey responses predict subsequent actual choices for a savings commitment programme and that behaviour in a laboratory trust game predicts successful loan repayment[69,70]. Neuroeconomists could extend this result by identifying neural markers of self-control — obtained either from social[71] or economic[55] domains — that can predict spending habits or debt management. It has been claimed that such mechanistic information about brain function is irrelevant because the neural data are not part of economic models[27]. However, if the out-of-sample predictive power of a model were enhanced by inclusion of neurobiological data, there would be clear empirical benefits. In other words, although there is already evidence that laboratory behaviour can be linked to everyday behaviour, adding a mechanistic layer — at the neurobiological level — would enhance our understanding of some traditional economic variables (for example, prices at which exchanges are made)[26].

Neuroscience may not only contribute to studies in economics but also to studies in other areas of the social sciences. Core field measures of interest in these areas include a range of societal outcomes: happiness, productivity, political preferences, health and social stability. These outcomes are usually assessed through accumulation of macroscopic techniques outside the laboratory (for example, surveys and economic indicators), even though the interventions that are used to shape those outcomes often have varied effects on specific individuals. Just as laboratory studies in experimental economics have inspired interventions in financial markets[72,73], studies in neuroeconomics may be useful for directing interventions in the applied social sciences. One way in which neurobiological concepts could be integrated with large-scale survey data may be through assessing genetic influences on brain function, and indeed the collection of genetic data in social science research is increasing in popularity[49,74].

Research on brain function may also aid the development of customized interventions for different subpopulations. Cues that nudge behaviour — such as encouraging reflection on one's likely activities at a future date — can alter economic preferences (for example, through temporal discounting[75]) and subsequent real-world choices. How a given person responds to these cues may be shaped by demographic differences, such as gender, by dysfunction or disease state or even by computational style[39]. There are both philosophical and methodological hurdles to overcome before neural measures can be related to such outcome measures: for example, can the subjective experience of happiness be compared between subjects and, if so, how can it be measured neurologically in practice[26]? However, a core goal of neuroeconomics should be to design studies that would assist both neuroscientists and economists in assessing the benefits (and limitations) of expanding the predictive range of either discipline beyond individual choices to aggregate-level outcomes[76].

Balancing the demands of the parent disciplines. Of course, achieving the potential gains from these three pursuits (targeting general neural mechanisms, increasing the focus on individual differences and moving beyond the laboratory) requires more than comprehensively assessing neuroeconomics in isolation. The future of neuroeconomics will also be shaped in relation to the evolution of its parent disciplines — neuroscience and economics.

Two of the more daunting challenges for neuroeconomics are methods-based and thus, perhaps unsurprisingly, shared by neuroscience. First, the rapid acceleration of research has necessitated new methods for effectively accumulating and synthesizing research results[77,78]. The development of such methods will aid neuroeconomics in

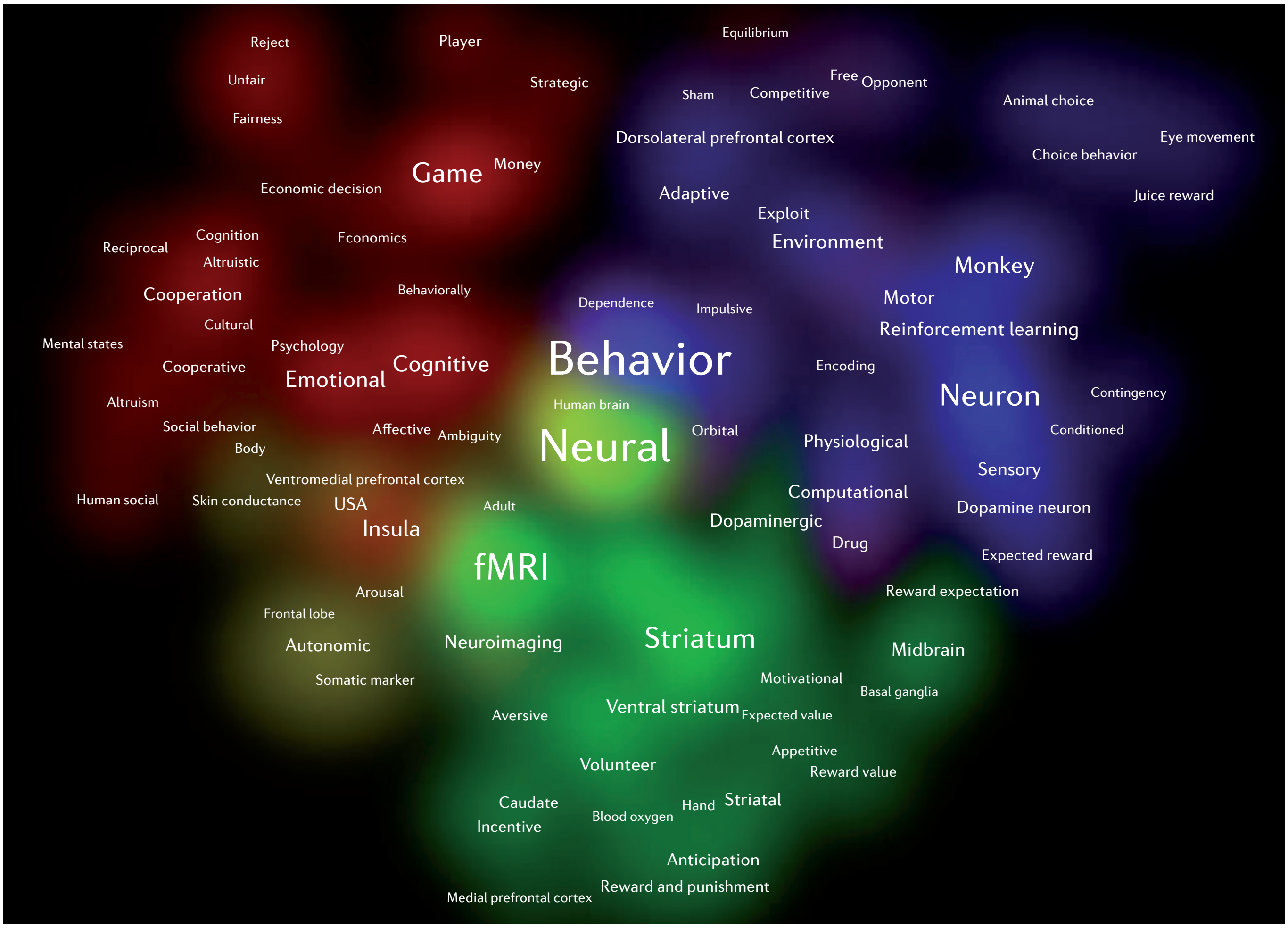


Figure 4 | **Knowledge domains in the neuroeconomics literature.** From a set of 27 review articles in neuroeconomics, we identified all unique references to other articles in the primary literature ($N = 259$). The abstracts of those references were analysed using semantic network analyses, which created a map of conceptual terms within that literature. The relative size of terms is proportional to their frequency of occurrence; for example, 'neuron' and 'fMRI' occur relatively frequently, whereas 'caudate 'and 'strategic 'do not. Terms that frequently co-occur within an abstract are positioned closely together (distance calculated by a positioning algorithm); for example, 'dopamine' and 'expected reward' often co-occur. Colours indicate groups that were formed by an algorithm that identifies densely connected clusters; these groups reflect the topical themes around which the neuroeconomics literature is organized.

routinely conveying findings to economics. Second, the most common experimental technique in neuroeconomics is functional MRI (fMRI), and the sustained popularity of fMRI is a mixed blessing: it is non-invasive and provides a view of the spatial distribution of the cognitive processes in humans, but it cannot provide insight into the neuronal physiology of these processes. All research agendas under the umbrella of neuroscience — including neuroeconomics — must find ways by which fMRI results can be generalized to other neural measures[79,80]. Neuroeconomics has already made significant progress in this direction with substantive contributions from single-unit recording and other techniques.

A third challenge lies in overcoming mutual misperceptions about the nature of research in the neural and social sciences. A common misconception in neuroscience is that economic models fare poorly at predicting behaviour ('economic models only work with rational behaviour'), and economists sometimes misconceive neuroscience methods as poorly executed or overly simplistic ('brain scans are eye candy'). Recent prominent papers in cognitive neuroscience and economic theory should clear up the misperceptions of limited scope or lack of sophistication. Indeed, recent empirical studies in neurophysiology[81,82] and fMRI[83,84], as well as their associated statistical analyses, demonstrate rich potential for further research and education[15,85]. Nevertheless, greater effort should be made to exploit the direct links between some components of the data analyses in economics and neuroscience (for example, time series analysis, which is central both to financial econometrics and fMRI data processing[86,87]). Similarly, economic theory has many models that incorporate and explain various behavioural phenomena observed in both the laboratory and the field[88–90]. Neuroeconomists should pay attention to these models to overcome mutual misperceptions.

Last, the incentives of an aspiring student or faculty member in neuroeconomics must be considered. Although neuroeconomics may be stimulating as an interdisciplinary research venture, the career of individual researchers still hinges on publishing only in journals that are deemed relevant by their primary discipline. A mechanism for encouraging cross-fertilization of research would require universities to appreciate publication records that include both neuroscience and social science journals. For example, universities are already constructing interdisciplinary cognitive neuroscience centres, and we are hopeful that these centres will embrace research that includes economics and other social sciences, in the best tradition of interdisciplinary research[91,92]. We further anticipate connections in the opposite direction, with business and economics departments recognizing the relevance of neuroeconomics research. In addition, new funding mechanisms, new courses, seminars and collaborative laboratory spaces are examples of ways in which interdisciplinarity can be promoted. Efforts, on any level, to facilitate interdisciplinary work will certainly incentivize future students to choose neuroeconomics as their field of interest and improve the quality of future research in neuroeconomics.

Neuroeconomics as a locus for translation

Neuroscience has the potential to connect to the social sciences in several ways. Many of the topics that are most central to social science research — such as the nature of individual choice, the factors that shape social interactions and the ways societies respond to unexpected events — would benefit from an improved understanding of the neurocognitive mechanisms underlying them. The depth of disciplinary specialization that characterizes modern academic institutions has presented barriers to connections between the neural and social sciences. However, our analyses show that there are reasons for optimism. Neuroeconomics has become an interdisciplinary research community in which influential research groups have a balanced composition of members from neural and social sciences. Moreover, neuroeconomics research includes publications in journals that cover diverse and otherwise unrelated areas of science (from theoretical finance to clinical medicine), demonstrating an ability to reach throughout the scientific milieu and connect different networks.

At the small-scale level of laboratories and research projects, neuroeconomics has provided proof-of-concept evidence that neuroscientists and economists can interact with mutual benefit. How might local connections — such as conversations between members in an interdisciplinary laboratory — scale up to facilitate stronger integration of the neural and social sciences? In our view, neuroeconomics holds particular promise for providing a *lingua franca*, or trade language, that facilitates communication between disparate cultures. Trade languages arise when two or more cultures come into unexpected contact, at a site where individuals move back-and-forth between that site and their home culture, and when transactions are mutually beneficial. Neuroeconomics acts as such a locus — it enables individuals from different scientific disciplines to collaborate towards the solution of a common problem. Its 'language' does not provide the full range of expression of either discipline in isolation, but it does enable core concepts from one discipline to move into the other.

Our suggestions for the three pursuits on which neuroeconomics should focus fit with this model for translation of knowledge. If the understanding of the neurobiological underpinning of behaviour continues to improve, there must also be an interdisciplinary mechanism in place by which this biological knowledge can be transferred across the boundaries of behavioural disciplines. With success, neuroeconomics will identify foundational concepts — ones that make joint predictions about biology and behaviour — that can be readily translated to other social sciences. In this way, neuroeconomics can serve as a directive for dialogue between neuroscience and other disciplines.

Clement Levallois and Ale Smidts are at the Rotterdam School of Management, Erasmus University, 3062 PA, The Netherlands.

Clement Levallois is also at the Erasmus Virtual Knowledge Studio, Erasmus University, 3062 PA, The Netherlands.

John A. Clithero is at the Division of the Humanities and Social Sciences, California Institute of Technology, Pasadena, California 91125, USA.

Paul Wouters is at the Centre for Science and Technology Studies, Leiden University, Leiden, 2300 AX, The Netherlands.

Scott A. Huettel is at the Department of Psychology & Neuroscience, and the Duke Center for Interdisciplinary Decision Sciences, Duke University, Durham, North Carolina 27708, USA.

Clement Levallois and John A. Clithero contributed equally to this work.

Correspondence to S.A.H. and A.S.
e-mails: scott.huettel@duke.edu; asmidts@rsm.nl

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Glossary

Community detection
(Also known as cluster analysis). The identification of groups of relatively tightly connected nodes in a network on the basis of an algorithmic analysis of the graph formed by the nodes and edges.

Connected component
In a network, a group of nodes that are all connected either directly or through other nodes.

Expected value
The weighted, probabilistic average of all possible values for an uncertain reward.

Natural language processing
A set of methods from computational linguistics to extract meaningful features (such as the language or the topic) of a corpus.

Out-of-sample predictive power
When fitting a model to data, the predictive power — or generalizability — of that model can be tested on data not used to estimate the model (that is, out-of-sample data).

Semantic network analytic
Application of the methods and tools of network analysis to textual data; it creates networks based on semantic relationships or co-occurrences of terms in a text corpus.

Temporal discounting
(Also known as delay discounting).The tendency to reduce the subjective value associated with rewards as the delay until their receipt increases.

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Competing interests statement

The authors declare no competing financial interests.

FURTHER INFORMATION

John A. Clithero's homepage: http://www.hss.caltech.edu/~clithero
Duke Center for Interdisciplinary Decision Sciences: http://www.dibs.duke.edu/research/d-cides
Erasmus Center for Neuroeconomics: http://www.erim.eur.nl/neuroeconomics
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