

Towards a brain-to-society systems model of individual choice

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Abstract Canonical models of rational choice fail to account for many forms of motivated adaptive behaviors, specifically in domains such as food selections. To describe behavior in such emotion- and reward-laden scenarios, researchers have proposed dual-process models that posit competition between a slower, analytic faculty and a fast, impulsive, emotional faculty. In this paper, we examine the assumptions and limitations of these approaches to modeling motivated choice. We argue that models of this form, though intuitively attractive, are biologically implausible. We describe an approach to motivated choice based on sequential sampling process models that can form a solid theoretical bridge between what is

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known about brain function and environmental influences upon choice. We further suggest that the complex and dynamic relationships between biology, behavior, and environment affecting choice at the individual level must inform aggregate models of consumer choice. Models using agent-based complex systems may further provide a principled way to relate individual and aggregate consumer choices to the aggregate choices made by businesses and social institutions. We coin the term “brain-to-society systems” choice model for this broad integrative approach.

Keywords Choice models · Dual-process models · Agent systems · Sequential sampling process models · Motivated adaptive behavior · Neuroscience · Neuroeconomics

1 Introduction

This paper focuses on individual choice in contexts where cue-induced processes, shaped by human evolution and tied to biological drives, carry a significant weight in decision making and behavior. Referred to as *motivated adaptive behaviors*, these processes span a wide range of choices, e.g., from food and companionship to strategies for minimizing physical and psychological discomfort (Kalivas and Volkow 2005). We will be using food choice as the primary domain of interest, as this area has seen much research development regarding these motivated adapted behaviors (Broberger 2005). Some of these biologically driven processes are also involved in the less adaptive case of addiction; in some circles, it has been argued

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that today's problem of overweight and obesity represents a special case of addiction learned early on in childhood where highly caloric food serve as potent reinforcers that activate neural systems that largely overlap with those involved in addiction to substances (Volkow and O'Brien 2007). Guided by brain systems that have emerged early on in human evolution, impulsive *cue-induced processes* set the stage for individual choice as being a reflex-like conditioned response to cues, whether from the external environment or from internal signals, that lead to choice based on a learned repertoire of adaptive behaviors (Kalivas and Volkow 2005; Shiv et al. 2005). In the domain of food, it seems that such repertoire, which originally evolved to adapt to a scarce and uncertain food supply, has lost some of its fitness value with the ubiquitous presence of high-caloric food in the modern industrialized society where impulsive appeal is economically, socially, and culturally reinforced, leading to such problems as obesity.

Humans, however, have the capacity to regulate behavior in a flexible and goal-directed manner through their exercise of will power and self-control (Strack et al. 2006). They can engage in deliberate and effortful acts to overcome maladaptive cue-induced impulses. This capacity is linked to *executive control processes* which include inhibition, decision making, goal selection, and planning and are enabled by more recently evolved brain systems. It is possible, however, that a person's ability to engage in such executive control processes is itself vulnerable to environmental influences. Many imperatives of everyday personal, familial, and professional life in modern society render particularly fierce the competition for the cognitive resources necessary for constraining impulsive responses.

Thus, the biological influences on motivated behavior call for models of individual choice that are biologically plausible and consider the environments in which choice occurs (for a similar argument, see Cacioppo et al. 2000). Among existing individual-level models of choice, dual-process models represent one of the most serious attempts to account for some of the differentiated processes associated with motivated choice, respectively, encapsulating the two types of processes in the labels of "hot" and "cold" modes and considering environmental cues among the set of possible moderators of the relative dominance of each mode in different conditions. In this paper, we review the assumptions of the dual-process models in Section 2. We examine their limitations in light of contemporary knowledge about the brain systems involved in food choice in Section 3. In Section 4, we highlight a different class of choice models, namely the sequential sampling process models (SSPMs; see Otter et al. 2008, in this issue) as more biologically plausible. Having become influential in both psychology and neuroscience, these models have more potential to form a solid theoretical bridge between neural models of brain systems and behavioral models of individual choice by taking into consideration environmental inputs in the choice process. We address in Section 5 developments that are needed in order to inform aggregate models of consumer choice, as well as supply and demand business models, with the complex and dynamic relationships between biology, behavior, and environment modeled at the individual level by SSPMs. We suggest further that such an approach, linking biologically informed aggregate models of consumer choice to model of supply/demand business choices, can be extended to other economic, social, and political agents that contribute to the balance of opportunities and constraints afforded by the environment in which individual

choice occurs. Agent-based adaptive complex systems models appear to be a promising analytical platform for examining in some principled way the relationship between aggregate models of consumer choice/demand and the aggregate choices made by businesses and all other agents involved. We coin the term “brain-to-society systems” models for this broad integrative approach to choice and provide a schematic representation of its core components in Fig. 1.

2 Basic assumptions of dual-process models of individual choice

Dual-process models of individual choice are known under such labels as “hot vs. cold cognition” (Mischel et al. 1972), central vs peripheral (Petty and Caccioppo 1986), heuristic vs systematic (Chen and Chaiken 1999), and “reflective vs impulsive systems” (Strack et al. 2006). For the sake of brevity, we encapsulate these two modes using the labels “hot” and “cold”. Two distinct types of information processing are involved: the “cold” mode being rational and analytic, reflective, relatively slow in processing, and consistent across contexts and the “hot” mode being emotional, impulsive, and rapid in its decision making. Depending on the model, competition between these two modes can be parallel (e.g., “the emotional system overrides the rational system”) or serial (e.g., “while in an emotional state, decisions tend to be impulsive and irrational”). Competition is usually modeled using the assumption that as one system increases its influence on behavior, there is a concurrent decrease in the influence of the other. Factors tied to individuals, tasks,

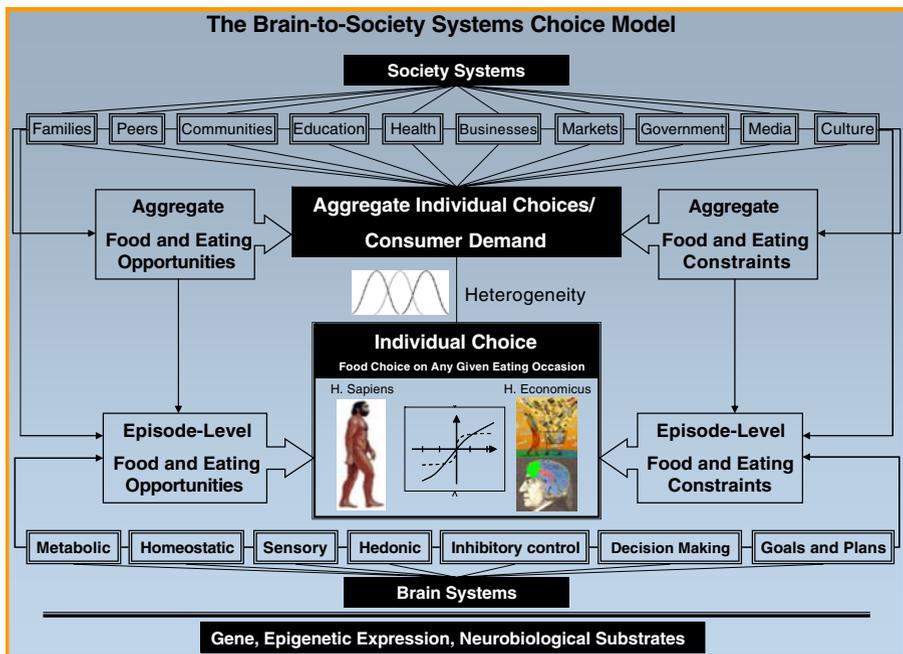


Fig. 1 The brain-to-society systems choice model

as well as environmental cues and other contextual effects, moderate whether one or the other mode is more likely to prevail.

In most conceptual models under the “hot” mode, affective processes that are biologically wired such as hunger, sensations, pleasures, emotions, and stress are believed to be looking for the presence or absence of stimuli to approach or avoid in the environment. This discrete process that resembles an “on/off” switch may translate into a value function with a stepwise pattern (Desmeules et al. 2008). Under the “cold” mode, attention-demanding deliberative processes assess options with a goal-based perspective to help a person make sound and deliberative decisions with a broad, flexible, and long-term perspective, possibly assessing their value along the lines of standard expected utility models or prospect theory and ensuring more flexible choices than the reflex-like choice outcomes posited under the “hot” mode. In most dual-process models, an individual’s utility function is derived from integrating (1) utility arising under affective processes in the “hot” mode and contributing to choice in a non-normative direction, with (2) the “cold” deliberative processes that examine the expected utility or prospect value of each option.

A limited number of formal dual-process models have been proposed to specifically account for cue-induced processes, self-control, and willpower (Bernheim and Rangel 2004; Fudenberg and Levine 1999; Faruk and Pesendofer 2001; Laibson 2001; O’Donoghue and Rabin 1999). Models of self-control typically take into consideration the cost and limited supply of attention and willpower, as well as time discounting functions to reflect a natural preference for immediate over long term outcomes (Laibson 2001; Loewenstein and O’Donoghue 2004; O’Donoghue and Rabin 1999). A cue-induced process model for addiction (Bernheim and Rangel 2004) bases the transition between “hot” or “cold” modes on prior experience and on past efforts to protect against the emergence of maladaptive behavior. All these models consider self-control and willpower as a limited resource expanded by deliberative processes in overcoming naturally arising affective processes. They make predictions about when people may show “steeper” hyperbolic discounting, or stronger temptation (dis) utility, or are more likely to experience “hot” states. It is also noteworthy that the individual value function in most of these formal models remains anchored in the traditional deliberative-process-based utility function with a “penalty” component to accommodate for “hot” mode non-normative decisions.

3 Limitations of dual-process models

Specifying the biological basis of adaptive motivated choice requires bridging the gap between the molecular/genetic level of neural pathways involved in metabolic and homeostatic systems, with others involved in sensory-perceptual processing and hedonic responses, as well as with the systems involved in inhibitory control, decision making, and the longer term setting of goals and plans (see the lowest two sections in Fig. 1). As will be briefly reviewed, in the food domains, on any given eating occasion, the seemingly simple choices we reportedly make more than 200 times a day (Wansink 2006) are fraught with extensive crosstalk, numerous reciprocal connections, and on-going integration of signals from the internal and external environments processed in a diversity of brain systems (Berthoud 2002). These complex interactive

and dynamic relationships between biology, behavior, and environment, we will argue, are not satisfactorily accounted for in dual-process choice models

3.1 The brain systems involved in food choices

In humans, the metabolic and homeostatic systems involved in the regulation of food behavior, energy storage, and energy expenditure involve a network of interacting feedback mechanisms at the level of the hypothalamus, brainstem, higher brain centers, in communication with peripheral signals from stomach, gut, liver, thyroid, and adipose tissue, with a rich diversity of hormonal signals are involved (Berthoud 2002). They are designed to guide food choices on each eating occasion and over longer time spans so as to ensure the appropriate nutritional and caloric variety and quantity tied to an omnivorous nature.

Metabolic and homeostatic brain systems interact in complex ways with sensory and hedonic systems. For instance, visual and olfactory responses to cues signal food as edible objects, and they have the power to trigger a cascade of metabolic and homeostatic responses to prepare for eating. With taste, these convey information on the food's palatability which is then integrated with both short-term and long-term signals about nutritional states. These processes are further modulated by emotions as well as by diverse signals such as the sleep/wake cycle or stress level (Dubé et al. 2005).

Certainly, one of the strongest drivers of food choice and eating is the rewarding nature of food defined in hedonic brain systems. Neuroimaging studies of the brain response to food imagery indicate that the human brain has automatic approach responses to food by comparison to non-food objects (e.g., Killgore et al. 2003). This research further shows that these responses can be significantly modulated by marketing actions, such as advertising (McClure et al. 2004) and pricing (Knutson et al. 2007; Plassmann et al. 2008). The reinforcing properties of various food items are what might be biologically stamped in learned habits and preferences (Kalivas and Volkow 2005). Dopamine is the central neurotransmitter implicated in reward processing, motivational states, and habit learning (Wise 2004). Dopaminergic neurons carry a signal for errors in the prediction of reward that is critical to both learning and decision making (Schultz 1998). Their activity is modulated by anticipated upcoming reward (Knutson et al. 2007) and by the perceived relative value of options (Padoa-Schioppa and Assad 2006). Dopamine-associated learning mechanisms may also be involved in social norm compliance (Spitzer et al. 2007; Klucharev et al. 2008).

A key challenge for the brain then is regulating motivated behavior in a flexible and goal-directed manner. Those aspects of cognition that allow selection of context-appropriate behavior are collectively known as *executive control processes*. As befits the name, executive processes are considered to play a role in modulating brain functions, inhibiting some processes and potentiating others in order to shape behavior. Executive control may be particularly challenging when people are faced with decisions about food. Successful dieting, for example, requires not only inhibition of the impulsive responses triggered by food-related cues but also strategic planning of future actions while maintaining flexibility to adapt to the immediate context.

The brain region most commonly associated with executive control is the prefrontal cortex (PFC). Broadly speaking, the core functions of the PFC are to

inhibit inappropriate behaviors and to potentiate desired behaviors in a goal-directed manner. Damage to the prefrontal cortex, or dysfunctions of the neurotransmitter systems that innervate the prefrontal cortex and modulate its activity (e.g., dopamine and serotonin), are associated with poor impulse control and disinhibited behaviors. Control signals from these regions, which ultimately connect and communicate with subcortical areas involved in feeding such as the hypothalamus, may be particularly important in the control of human food intake in the modern environment of affluent societies filled with food with high caloric content. The PFC is not a unitary structure, and subcomponents of PFC influence food choice and behavior at several dissociable levels. The orbito-frontal PFC specializes in emotional processing and inhibitory control; it has been shown to be critical when learning about rewarding and punishing stimuli (O'Doherty et al. 2001). The ventromedial PFC, highly interconnected with other ventral brain regions associated with emotional and affective processing, such as the amygdala and insular cortex, plays a central role in decision making under uncertainty (Bechara and Damasio 2004). The dorsolateral PFC (DLPFC) plays a critical role in working memory, is involved in setting up general rules for behavior (posterior), and contributes to abstract aspects like mental simulation and internal comparison (anterior). Regions of DLPFC are also often involved in decision making, especially when evaluating probabilities, reasoning about options, and selecting responses (Huettel et al. 2005). The DLPFC is particularly important for one's ability to follow plans that require temporal ordering of behavior.

In sum, neuroscience research, both in non-human animals and human subjects, suggests that there are deep and elegant links among all brain systems involved on every eating occasions, these brain systems guiding individuals in their responses to the set of food and eating opportunities and constraints arising from signals received from the internal and external environment. In food and other domains of motivated behavior, bridges have to be developed between these neural models of brain systems and behavioral models of individual choice.

3.2 The limited biological plausibility of dual-process models

From the evidence reviewed above, there is little basis to view brain systems for cognition and emotion as being separable, nor is there evidence to support the view of their competitive or serial relationships assumed in the dual-process choice models. In fact, by imposing a clear and permanent divide between the “hot” and “cold” modes, dual-process models fail to acknowledge a critical evolutionary advantage in making choices—namely, the ability to flexibly adjust decision parameters to context whether it involve the speed of decision making, the cognitive resources used, or the brain systems called upon. Second, while dual-process models account for inter-temporal choice and progressive exhaustion of willpower over time, they do not take into account the short- and long-term dynamics involved in the complex homeostatic and hedonic processes that modulate many temporal parameters involved in food choice on any specific eating occasion.

Another important limitation of the dual-process models is the assumption that all the different “hot” states impact choice in the same manner. In the domain of food, taste sensations, hunger and fullness, food-borne pleasure, cravings, and reward

responses are all subsumed under the “hot” mode and treated alike in their effect on food choice. Yet, there is little doubt that critical differences exist in the nature, direction, and timing of their impact on food choice. Similarly, dual-process models consider sadness, anger, cognitive load, anxiety, arousal, and regret as non-differentiated emotional states that pull behavior away from the rational mode. However, this assumption is inconsistent with neuroimaging and pharmacological data.

One of the least tenable assumptions of the dual-process models in the context of food choice is that decision-making behavior associated with the rapid emotional mode is maladaptive. Powerful affective reactions of all types which have evolved to guide food choice, jointly with executive control processes, have been, and arguably remain to a large extent, highly adaptive (Broberger 2005). At the aggregate level, *Homo sapiens* and its predecessors as well as the modern *Homo economicus* have quite successfully relied on them since it has only been since a few decades—proportionately less than 1 s in the 1 day of human evolution—that the set of opportunities and constraints afforded by the environment appeared to have surpassed the threshold that biology can handle, with the body mass index having remained relatively stable at the population level until then.

Finally, in dual-process models, internal or external environmental cues are not considered as being an intrinsic component of the choice process as the review of brain systems above suggests. Instead, they are among the set of possible moderators that determine which mode becomes dominating in different conditions (e.g., Shiv and Fedorikhin 1999). This view is very different from considering for instance the internalization of social norms as being an intrinsic component of the choice process, as demonstrated in food choice research (Herman et al. 2003) and in other areas (Sen 1993). In sum, the limitations of dual-process models bear on their implausibility from the perspective of the brain’s structure and function as well as from their exclusion of internal and external signals that are not strictly attached to the choice option as intrinsic part of the valuation process.

4 Sequential sampling process models

One promise of neuroscience is that models of brain function can provide insight into individual-level behavior at the molar level (i.e., the average of an individual’s choice over repeated episodes) by suggesting choice algorithms based on local neural processing in response to features of the choice options at the level of each episode and taking into account internal and external signals that determine the set of food and eating opportunities and constraints afforded by the environment (Sugrue et al. 2005). From this perspective, a biologically plausible model of choice will have to be conceived at the episode-level and account for the possibility that all brain systems are called upon to guide one’s response to environmental cues.

We propose SSPMs (Ashby and Townsend 1986) as promising biologically plausible frameworks for motivated choice. SSPMs typically make three fundamental assumptions: (1) the evidence favoring each alternative is accumulated and integrated over time, (2) the process is subject to random fluctuation, and (3) a decision is made when sufficient evidence has accumulated favoring one alternative over the other at a certain threshold level at which accurate decision can be made

with a tolerable level of uncertainty. Research on decision field theory (for a review, see Busemeyer and Diederich 2002) has accumulated a rich body of evidence of the psychological processes suggested by SSPM in the context of value-based judgments, e.g., attitudes, preference, or choice for two and multiple alternatives as well as for multiple-attribute alternatives.

In modeling value-based judgments, psychological SSPMs move beyond the consideration of the instantaneous utility of alternatives and a focus on choice outcomes by considering deliberative processes. Instead, SSPMs propose to let pre-choice processes formally inform our understanding of a choice problem by arguing that it is not only the intrinsic utility of the alternatives that drive choices but also the nature of information that accumulates over time until a decision threshold is reached. This deliberation process is manifested by indecisiveness, vacillation, inconsistency, attentional shifts, conflict, and cognitive limitation—all phenomena common in motivated choices (Busemeyer and Townsend 1993).

According to value-based SSPM, value-based judgments are derived from a stochastic process of accumulation and integration of information over the time which determines dynamically the evaluation of the choice options and the setting of a decision threshold (Diederich 1997). In the context of multiple attributes options, SSPM assume that the diffusion process has a specific input valence for each attribute. At any particular time during deliberation, the decision maker's attention process may focus on one attribute and, during the next moment, switch to operate on the process for another attribute. While attending momentarily to a particular state at a given moment, the decision maker compares consequences produced by each action under that state. These momentary comparisons are integrated over time to form an overall preference for each action until a decision criterion is reached. As described in more detail by Otter et al. (2008, in this issue), this feature of SSPMs can account for such well-known violations of Luce's choice axiom as the similarity, compromise and attraction effects (Böckenholt 2007). This feature also predicts empirical reversals between choices and prices and between buying and selling prices (Johnson and Busemeyer 2005).

We believe that SSPMs are better candidates than dual-process models at bridging neural models of brain systems to individual choice in food and other domains of motivated behavior. Food choice and behavior on any eating episode result from the flexible, progressive, and cumulative accumulation and integration of internal and external signals until a decision criterion is reached. Such signals could encompass momentary state of caloric and nutritional deprivation and satiation, nature and intensity of food and food cues, and affective states. In fact, research on the influence of approach and avoidance motor action on food intake would suggest that the activation of non-food-related motor systems could also be integrated (Förster 2002). Signals are also conveyed by episode-specific decision conditions, goals, or tasks, as well as signals reflecting individuals' personal characteristics, preferences, and habits related to general or food-specific approach and avoidance such as internalized social norms that prevail on different occasions (see Fig. 1).

Altogether, the nature, intensity, and time course of these internal and external signals progressively accumulated and integrated along the choice process reflect the balance between food and eating opportunities and constraints that determines

individual choice at the episode level. Beyond the intrinsic attributes of the choice options, the need for these attributes, the degree of goal achievement produced by an option, even a person's general or episode-specific approach or avoidance predisposition may change the relative motivational value of each option at any given point in time along the decision process and determine when the decision threshold is reached (Sengupta and Zhou 2007).

Another feature of SSPM that makes them biologically plausible is the “scale-free” nature of their ability to account for all facets of the temporal dynamics involved, a consideration that goes beyond what self-control and other cue-induced dual-process modes have been able to do. Specifically, beyond temporal discounting and exhaustion of self-control or will power overtime, this feature of SSPM enables them to accommodate the large variability that exist in the timescale of information conveyed by the various brain systems that modulate many components of the food choice process, ranging from on-going signals being sent from the gut to the brain that change the reward value of food as it is consumed (Small et al. 2003), to changes in need states associated with feelings of hunger (Read and van Leuwen 1998), to the long-term interval involved in craving for food not consumed for a long time, and to the lifelong learning of well-entrenched preferences and habits.

The central role given to time in SSPMs also provides insights on why resisting the appeal of ubiquitous food cues is challenging: It has been suggested that information conveying immediacy—as the taste and smell of food—engages more posterior ventromedial prefrontal cortex (VMPC; including anterior cingulate, basal forebrain, and nucleus accumbens), whereas information conveying delay—such as the long-term consequence of health—engages more anterior VMPC cortices (i.e., frontal pole). Signaling via the posterior VMPC is associated with relatively fast, effortless, and strong affective signals, while signaling via more anterior VMPC is relatively slow, effortful, and of weak neuronal intensity (Bechara and Damasio 2004). If a decision is made as soon as a criterion decision is reached, sensory and vivid information are therefore more likely to contribute to the decision process than the slower consideration of long-term and abstract consequences.

Further evidence for the biological plausibility of SSPMs in food and other motivated choices can be derived from their application to the neurophysiology of simple sensory and motor systems involved in various perceptual judgments (e.g., Huk and Shadlen 2005; Rorie and Newsome 2005; Platt and Glimcher 1999). This line of work typically involves studies in which monkeys trained to discriminate noisy visual stimuli report their perceptual judgment using eye movement. By recording neural activity in visuo-motor pathways, it is possible to dissociate sensory representation and decision-making signals. Results show that the pattern of activation that accumulates over time in decision-related neurons reflects the animal's ultimate choice. Recently, Sugrue et al. (2005) proposed a conceptual framework for extending this line of work from sensory processing to value-based decision making such as those investigated by the psychological SSPMs reviewed above. While the detailed presentation of this framework is beyond the scope of the paper, it seems to be at the level of neural processes involved in the formation of value representation that social norms and other environmental cues are integrated to internal signals in determining behavior.

5 Moving towards a brain-to-society systems choice model

The complex and dynamic relationships between biology, behavior, and environment affecting motivated choice at the individual level must inform aggregate models of choice. It is at this level that consumer demand drives decisions by businesses and other society systems that shape the balance of eating opportunities and constraints in the environment in which individual choice occurs. Complex interconnections among multiple industries including suppliers, manufacturers, assemblers, distributors, and retailers require modeling frameworks that aid in making network decisions which facilitate learning and adapting one's organization in a constantly changing environment (Erden et al. 2005). When decision making is based on such noncomplex assumptions as linearity, sparse connectivity, static environments, and non-adaptive individual firm behavior, the true problems are often hidden and leave many opportunities for understanding and improving the underlying processes (DeSarbo et al. 2006).

Businesses make choices that shape supply and demand to maximize their objective functions (typically profits) while competing in the marketplace. In a complete system of supply and demand, choices made by both consumers and businesses are endogenous and require the joint examination of their separate and interdependent choices. Typically, structural models of demand assume that observed market data are equilibrium outcomes for rival firms given a demand specification (Chintagunta et al. 2006). Imposing the equilibrium conditions implied by the supply-side model allows estimating the parameters of the demand function. However, even for such seemingly simple issues as predicting the impact of food prices and income changes, say, on consumption and body weight, we need to go beyond current structural models of aggregate consumer choice models and their notions of utility maximization to capture effects of self-control problems and time-inconsistent preferences. Such models would be indispensable to predict and analyze the effects of market externalities resulting from higher taxes, insurance, and subsidies to correct for obesity-related costs.

The collection of biomarker information (including brain activity) and food consumption data on aggregate as well as individual levels in both their social, spatial, and temporal contexts will become increasingly commonplace and will play a crucial role in linking neurobiological and choice behavior research. Dynamic and spatial structural models are needed to handle these new data opportunities. We expect that agent-based complex systems models will play a crucial role in providing the needed analytical platform for examining the relationship between consumer demand and choices made by businesses and other agents involved such as policymakers. Multi-agent systems are computational systems in which multiple autonomous agents work together to perform a set of tasks to satisfy a set of goals. These systems may involve computational agents that are homogenous or heterogeneous; they may involve agents either having a common goal or having goals that are distinct or even contradictory. Broad fundamental issues that have been studied by multi-agent systems include cooperation, coordination, conflict and communication, negotiation in competitive and cooperative situation, distributed consensus, resource allocation, multi-agent cooperative reasoning, distributed search, multi-agent planning, social structure, organization, and organizational knowledge (Axtell et al. 2002; Epstein 2002; Hammond and Epstein 2007).

6 Conclusion

Creating biologically based models of choice that takes into account not only the environment in which individual choice occurs but also the societal choices that shape such an environment poses daunting and manifold challenges. It will require theoretical, methodological, and analytical developments. It will also necessitate the development of a new and integrative infrastructure for dealing with information about choice behavior drawn from many levels and many sectors. In spite of the magnitude of the undertaking, we are convinced that it is worth modeling the wide spectrum of biological and societal factors—as they spread from the ‘brain’ to ‘society’—in ways that traditional research design cannot accomplish. We hope that this article will set forth a framework for deriving choice models that consider motivated adaptive behaviors in their societal context.

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