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PERSPECTIVE

Simon's bounded rationality

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Abstract
This note in the *Milestones* series is dedicated to the paper *"A Behavioral Model of Rational Choice"*, written by Herbert Simon and published in 1955 on the Quarterly Journal of Economics.

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JEL Classification D01 · D91

1 Introduction

Bounded rationality in perception and behavior is a very popular topic in several disciplines, especially economics, management, psychology, and computer science. The ubiquity of this topic is explained by the relevance of human decisions in many areas of research.

In 1955 Herbert Simon published on the *Quarterly Journal of Economics (QJE)* the article *"A behavioral model of rational choice"* (Simon 1955), which contains the first formalization of a choice procedure performed by a boundedly rational economic

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agent. The relevance of Simon's work is certified by numbers: as of September 2023, according to *Google Scholar*, this paper has been cited 23,991 times. Here we celebrate this milestone of the economic literature by offering a perspective on the wide range of concepts it addresses, and disclosing some of the most relevant streams of research in economic theory inspired by it.

The paper is organized as follows. In Sect. 2 we quickly discuss the scientific vocation of Simon. Section 3 contains an overview of the main notions of rationality in preferences, choices, and decisions, as they were addressed before Simon's pioneering work. In Sect. 4 we inspect the model of choice proposed by Simon in 1955, and disentangle its main innovations. In Sect. 5 we analyze Simon's scientific legacy, and examine several contributions in theoretical and experimental economics that have been influenced by his seminal paper. Section 6 collects concluding remarks.

2 The author

Herbert Alexander Simon was born in Milwaukee in 1916, the second son of a German electrical engineer and an American pianist. As he revealed in his autobiography for the Nobel lecture, his home—full of books, paintings, and music records—and his family—often engaged in political and scientific debates—passed on to him a passion for culture and science. Simon's interest for human behavior was also fostered by his uncle, Harold Merkel, who studied economics at the University of Wisconsin, wrote many books in economics and psychology, and pursued a career in the National Industrial Conference Board.

Simon's scientific vocation has been influenced by several eminent scholars who crossed his academic path. During his graduate and doctoral studies in political science, which ended in 1943, he was supervised by Henry Schultz, one of the sixteen founders of the Econometric Society. Schultz was particularly focused on a more rigorous formalization and measurement of economic phenomena, such as the demand of agricultural commodities. He moved Simon to adopt mathematical and statistical tools to investigate institutions, firms, and consumer's decision making.

In 1942 Simon joined the Illinois Institute of Technology in Chicago, and attended (at the University of Chicago) the Cowles Commission, an organization interested in the connection among economic theory, mathematics, and statistics. At that time, the Commission was also attended by other talented economists, such as Trygve Haavelmo, and Jacob Marschak. Simon, during this fervid academic experience, faced many emerging statistical and economic approaches, such as novel econometric techniques, causal ordering and identifiability, comparative statics and dynamics. In 1947 he published the book *"Administrative Behavior: A Study of Decision-Making Processes in Administrative Organization"* (Simon 1947), in which he provided an extensive behavioral analysis of decisions and hierarchies in public administration.

In 1949 Simon left Chicago, and founded the Graduate School of Industrial Administration at the Carnegie Institute of Technology. Here, in collaboration with some brilliant colleagues (such as Charles Holt, Franco Modigliani, and John Muth), he worked on dynamic programming techniques to formalize optimal rules of industrial decisions under certainty and uncertainty (Holt et al. 1955, 1960). These research activities, focused on the decision process of complex entities, played a major role in shaping Simon's scientific perspective, and stimulated him to write the paper we shall discuss in this note.

Starting from 1954, Simon gradually focused on the computational analysis of decision making, as well as on computer simulations of human perception and behavior. In 1957 the publishing house Wiley issued *"Models of Man"* (Simon 1957), a collection of mathematical essays, in which Simon offered an analytical perspective on human models of choice.

Apart from the mentioned publications, the author's scientific production includes many works in economics, psychology, artificial intelligence, and political science (Simon 1965; Newell and Simon 1972; Simon 1986, 1987). In 1978 he was awarded the Nobel Prize in Economics *"for his pioneering research into the decision-making process within economic organizations"*.

3 Classical notions of rationality

Modeling the very concepts of *rationality* and *bounded rationality* is a key step in several fields of research. In fact, there is massive strand of literature on this topic, which extends across many disciplines, from theoretical and experimental economics (Arrow 1990; Smith 2007), to finance and accounting (Patel et al. 1991; Barberis and Thaler 2003), to industrial organization (Spiegler 2004), and to economics and psychology (Simon 1986; Smith 1991).

In the economic formalization of individual preferences, rationality is typically encoded by properties of coherence of the representing binary relation. In fact, preferences are usually regarded as fully *rational* only if they can be described by a binary relation satisfying transitivity and completeness—the two classical *tenets of rationality*. One of the advantages of imposing these (rather restrictive) conditions is that, under suitable separability properties, preferences become representable by continuous real-valued utility functions (Debreu 1954).[1]

To account for uncertainty in decisions, Savage (1954) generalized the definition of rational preferences, and—harmonizing the advancements of Rasmey (1926), de Finetti (1937), and von Neumann and Morgenstern (1944)—proposed an axiomatic derivation of expected utility. More precisely, Savage determined a sufficient condition for the existence and the uniqueness of a probability distribution over the states of the world and a utility function over the consequences jointly describing an expected utility-maximizer decision maker (DM).[2]

In choice theory the concept of rationality was first formalized for single-valued deterministic choices by Samuelson (1938). The American economist argued that a DM is rational if he selects in any menu the unique alternative that is maximal

[1] The monograph of Bridges and Mehta (1995) contains a vast, albeit not updated, literature on utility representations of preferences. The collection of papers edited by Bosi et al. (2020) contains some recent contributions in the field of mathematical utility theory and ordered structures. See also Giarlotta (2019) for a vast survey on the current trends (of rationality) in preferences, choices, and utility maximization.

[2] This condition consists of the existence of preferences over acts (functions mapping the states of the world to consequences) that satisfy six behavioral properties and a purely mathematical axiom.

according to a linear order (a transitive, antisymmetric and complete binary relation). Nowadays choice functions that display this desirable property are called *rationalizable*. Later on, Arrow (1959), Richter (1966), and Sen (1971) extended the notion of rationalizability to the larger domain of *choice correspondences*, which allow the DM to select more than one item from each menu. In the meanwhile, Block and Marschak (1960) proposed a notion of *stochastic rationality* for (stochastic) choice functions, the so-called *random utility model (RUM)*.[3]

Despite the elegance and mathematical amenability of the formalization, the classical way to encode rationality in preferences, decisions, and choices fails to explain many observed behaviors. In fact, several theories from psychology and philosophy—sometimes predating Simon's scientific advances—have questioned its applicability. Already in the late 19th and early 20th centuries, members of 'heterodox' schools of economic thought—notably the Historical School in Germany and UK (e.g., Schmoller and Ingram), and the Institutionalist School in the US (see, e.g., Veblen 1898, and Mitchell 1910)—had criticized the psychological assumptions implicit in marginal utility theory and epitomized by the *homo oeconomicus*.[4] Later on, another important critique was raised by Katona (1951), who examined from a psychological standpoint many economic problems, such as investment decisions, consumption plans, and saving.[5] In the same period, the influential works of Guetzkow (1951), Guetzkow and Gyr (1954), and March (1955) analyzed the impact of non-rational economic agents in decision-making groups, such as business firms, government departments, and political parties.[6]

As a consequence, under the common hat of *bounded rationality*, many weaker declinations of rationality have been proposed over the years, with the aim to explain a larger portion of economic phenomena by modeling empirically observed behavioral biases. We believe it is not hyperbolic to say that a large part of these novel streams of research took their inspiration from Simon (1955)'s epistemic foundation of bounded rationality. In his seminal contribution, Simon presents theoretical models of choice in which the DM's decisional process may deviate from the classical paradigm of rationality, due to the limited computing capacity and the natural approximations of the human mind.

4 Simon's approach

All notions of rationality mentioned in Sect. 3 implicitly postulate a *"choosing organism"*.[7] This organism—henceforth referred to as a DM—is (unrealistically) endowed

[3] A *stochastic choice function* is a theoretical representation of choice datasets containing, for each menu, the probability that a given item is selected.

[4] An historical perspective on this critique is provided by Angner and Loewenstein (2012).

[5] We thank a referee for suggesting this historical background.

[6] This contemporary developments inspired the writing of Simon (1955). Indeed at page 1 of the manuscript the author states: *"Recent developments in economics, and particularly in the theory of the business firm, have raised great doubts as to whether this schematized model of economic man provides a suitable foundation on which to erect a theory - whether it be a theory of how firms do behave, or of how they "should" rationally behave."*

[7] The phrase "choosing organism" is extensively used by Simon (1955).

with almost complete information about the framing of the choice and a limitless computational ability, which allows it to select the item or the action maximizing its utility. As a matter of fact, at the beginning of the fifties, psychologists had already started questioning such imposing assumptions. Herbert Simon—a scientist interested in the behavioral features of individuals and organizations—translated a part of these developments into an economic language. Nowadays we speak of Simon's "bounded rationality approach", although the expression "bounded rationality" is never explicitly used in the manuscript—it only appears for the first time in Simon (1957). However, Simon provides an *ante litteram* definition of bounded rationality in the introduction of his 1955 paper:

> *Broadly stated, the task is to replace the global rationality of economic man with a kind of rational behavior that is compatible with the access to information and the computational capacities that are actually possessed by organisms, including man, in the kind of environments in which such organisms exist.*

In other words, Simon aims to implement an analytical model of "realistic" rational choice, which accounts for the limited computational capacities and information that affect the DM's perception in several situations. Simon is well aware of the gap between empirical findings and economic theory, and so he explicitly states that his mathematical formalization is not able to fully reproduce the advancements of psychology on human rationality. Nevertheless, drawing both on these existing empirical results and on some new considerations, he proposes a novel paradigm of choice, which effectively reproduces many widespread behavioral biases.

4.1 The basic framework

The main components of Simon's model are presented in Section I of the manuscript, entitled *"Some general features of rational choices"*.

The initial component is a set of *"behavior alternatives"*, denoted by A. However, this set is typically shrunk to a subset $\mathring{A} \subseteq A$ of *"considered"* or *"perceived"* alternatives, which collects all items in A that the DM is able or willing to take into account. This apparently innocuous assumption has stimulated a contemporary stream of research in economics on "limited consideration", which will be analyzed in Subsection 5.2.

Another component of the model is a set S of *"possible future states of affairs"*, comprising all consequences of the DM's choice. The relation between the alternatives and the consequences is described by a mapping from A to 2^S, which associates to each item a in A a set $S_a \subseteq S$ of consequences. Simon enriches this framework by also assuming that for each a in A, there may exist a probability distribution P_a over the elements of S_a, which expresses the likelihood $P_a(s)$ that the consequence s in S_a is obtained whenever a is selected.

A further component of the model is a *"payoff function"*, which describes the DM's evaluation of each possible consequence. The author states that this function is classically represented by a real-valued map defined on S. However, in the remainder of his paper this assumption is adapted to better reproduce human limited computation faculties.

Simon concludes the discussion on the topic by illustrating some rational choice procedures reported in Arrow (1951). First, he describes the *"max-min rule"*, which states that the DM selects the alternative maximizing the payoff of the worst possible consequence, that is, $\max_{a\in A} \min_{s\in S_a} V(s)$. A few years later this choice pattern will be investigated by Danskin (1966), and, several decades later, formally axiomatized by Gilboa and Schmeidler (1989) and Maccheroni (2002), among many others.

Then Simon outlines the *"probabilistic rule"*: the DM selects the item which maximizes the expected payoff over the feasible consequences, that is, $\max_{a\in A} \sum_{s\in S_a} V(s) P_a(s)$. Differently from the max-min, this rule requires additional information about the probability that each consequence realizes. This framework is a different formulation of the expected utility paradigm formalized by Savage (1954).[8]

Finally, according to the *"certainty rule"*, if the DM knows that each alternative a yields exactly one consequence s_a, then he chooses the one maximizing the payoff of the associated consequence, that is, $\max_{a\in A} V(s_a)$.[9]

These three choice procedures assume that the DM is endowed with either complete information about the consequences of each alternative, or full computational capacities and awareness of her preferences, or both. In the core of his paper, Simon modifies these very restrictive assumptions in order to build more realistic models of choice.

4.2 'Simple' models of rational choice

In Section II, entitled *"The Essential Simplifications"*, Simon questions the basic tenets of traditional choice models. Specifically, he observes that the DM's ability to identify all available alternatives, specify any potential consequences, and assign to them a payoff and a probability of occurrence is highly debatable and hardly confirmed by empirical and experimental evidence.

Simon even conjectures that an *"unconscious"* decision maker may perform better than a *"conscious"* one, who acts following the conventionally accepted choice procedures. As a matter of fact, it is now confirmed in many experimental settings (Acker 2008; Gigerenzer and Gaissmaier 2011) that poorly informed and unaware DMs obtain results that are close to the utility maximizing outcomes.

On the basis of these considerations, Simon introduces some key simplifications, which better reproduce the decision making process. First, the author examines a very simple payoff function, which has either two (1 and -1) or three (1, 0, and -1) values, respectively interpreted as either satisfactory/unsatisfactory outcomes or win/draw/lose situations. Using this simplified setting, the DM may select any alternative that goes beyond her *"aspiration level"*, providing a satisfactory (or win)

8 In the late 1940s and early 1950s there was a big debate—which involved all major theorists of the period, some of them based at the Cowles Commission—on whether economic agents do maximize or should maximize their expected utility in conditions of risk. This debate is investigated in Moscati (2016).

9 Note that Simon points out that in each of these models the set A (of available alternatives) can be replaced by the set $\mathring{A}$ (of considered alternatives).

consequence. To offer an economic intuition of this elaboration, Simon describes a situation in which an individual is willing to sell a house at any price higher than a given amount of dollars, called an *"acceptable price"*. The author argues that there are specific circumstances which favor the application of this model of choice: for instance, aspiration levels are likely to be applied when the alternatives are sequentially offered to the DM. Alternatively, the DM may first observe only the satisfactory consequences (contained in $S' \subseteq S$), and then select, among those considered, the alternative a in $\mathring{A}$ which triggers only satisfactory consequences, that is, $S_a \subseteq S'$.

The latter procedure is effective if there is a highly discerning map from A to S, which allows to identify alternatives yielding only a limited set of consequences. However, in a first stage of the process this map may be rather coarse, associating the whole set S of consequences to each alternative a. Thus, the previous model of choice can be modified by introducing an intermediate step, in which the DM—possibly in response to external shocks—refines the map from A to S to eventually discover which alternatives bring satisfactory consequences (or win outcomes). The author clarifies that the described decision process is naturally adopted by chess players, who enlarge or reduce the set of satisfactory outcomes of a given move after the opponent's action. Simon states that, under additional assumptions, this decision scheme may significantly shrink the number of admitted sequences of moves. For instance, following this procedure, the sequences of 16 moves in a middle game of chess can be reduced from 10^{24} to less than 100.

Simon further enriches his novel framework, and considers a more complex payoff-function V, which assigns a vector of values $V(s) = (V_1(s), \dots, V_n(s))$ to each consequence s in S. In this representation, each component of the vector $V(s)$ can be interpreted either as the utility of one of the individuals involved in a collective decision, or as one of the multiple criteria employed by the DM. This yields a partial ordering of pay-offs, which applies to a large variety of situations. Specifically, Simon considers a vector $k = (k_1, \dots, k_n)$, called a *"minimum guaranteed payoff"*, such that the DM is willing to accept any consequence s in S for which $V(s) \geq k$ (that is, $V_i(s) \geq k_i$ for any $1 \leq i \leq n$). As before, the DM may first look at all the consequences $s \in S'$ satisfying $V(s) \geq k$ for a given $k \in \mathbb{R}^n$, and then choose an item a that yields consequences aligned with her aspiration levels, i.e., $S_a \subseteq S'$ holds for a. The notion of a multivalued payoff function, followed by some innovative works such as Ainslie (1975) and Elster (1987), has inspired the formalization of *multi-self* choice models (Kalai et al. 2002; Ambrus and Rozen 2014), which aim to explain how individual decisions are performed when the DM ponders many distinct criteria.

The choice procedures examined above yield an innovative perspective on individual decision making, but are extremely general, and guarantee neither the existence nor the uniqueness of a solution. Therefore, Simon devotes the last two sections of his 1955 paper to examining which behavioral assumptions can be used to obtain feasible solutions.

4.3 Dynamic aspiration levels

In Sections III and IV, respectively entitled "*Existence and Uniqueness of Solutions*" and "*Further Comments on Dynamics*", the author makes some qualitative considerations, which can help to retrieve unique choices from the procedures based on simplified payoffs.

Specifically, whenever all options are sequentially presented to the DM, the selected alternative is the first that satisfies the aspiration level. Simon goes beyond this simple but illuminating explanation, and considers "*dynamic*" aspiration levels, which are updated on the basis of the decision steps. For instance, the minimum price at which an individual is willing to sell a house increases if many appealing proposals—which are lower than her initial threshold, but are quite close to it—are submitted for consideration. Conversely, a sequence of low bids may discourage the seller, and induce her to lower her acceptable price. Alternatively, assuming that the aspiration levels are fixed, the DM may update the set $\mathring{A}$ of considered alternatives, narrowing it in case she faces items that bring satisfactory consequences, and enlarging it whenever alternatives with bad outcomes show up.

The author suggests many possible dynamic extensions of the analyzed models. In fact, aspiration levels and the payoff function may depend on all the past iterations of the decision process. If we assume that the DM may perform her decision multiple times, the payoff function can be split into two components, which separately account for the *"immediate"* payoff, and the *"position"* payoff, related to the history of the decision. Alternatively, the payoff function may be affected by the past consequences that the DM already experienced.

It is worth noting that Simon not only proposes new paradigms of rational choice, but also contemplates the possibility to compare such models, and evaluate their rationality/plausibility. This pioneering intuition paves the way for the analysis of the "success" and the "testability" of models, as we explain in Subsection 5.5.

5 Simon's legacy

The concepts and notions explored by Simon (1955) have inspired a large amount of scientific contributions in economics, psychology, social sciences, and several related fields.

This consideration must be accompanied by two preliminary *caveats*. First, although the value of Simon's approach has always been recognized, only recently mainstream economic theory has extensively elaborated on his advances (Rubinstein 2008). Several explanations of the delayed impact in economics of Simon's bounded rationality approach have been suggested. For instance, his approach was probably too far from the mainstream framework—neither optimization, nor formal representations, nor axiomatic foundation—to attract the attention it deserved. Moreover, if computational costs are included in the DM's utility function, we are back to the standard maximization problem (Stigler 1961). Finally, the meaning of *"satisficing"* is so context dependent that the falsifiable behavioral implications of bounded rationality theory may be unclear.

Second, the notion of bounded rationality shaped in Simon (1955) is rather different from the behavioral program, fostered from one hand by the celebrated analysis of heuristics due to Kahneman and Tversky, and formalized, on the other hand, in the vast body of generalizations of the expected utility framework. Indeed, preference and utility maximization are absent from the explicit model shaped by Simon in his seminal paper, and choice is conceived of as the result of the application of simple decision making *rules* that take human computational limits for granted. This is also reflected in the author's efforts to replace, in his later writings, the expression *"bounded rationality"*—which may have a negative connotation—with the more neutral term *"procedural rationality"* (see, e.g., Simon 1987).[10] In contrast, the *"heuristics and bias"* theory originally proposed by Tversky and Kahneman (1974), and discussed in the Nobel lecture of Kahneman (2003), adds an automatic and intuitive decisional procedure—summarized by the so-called *heuristic principles*—to the standard utility maximization, and extends neoclassical models by directly modifying the form of the DM's utility function and/or introducing new constructs, without stating a definite axiomatic system (see, e.g., Laibson 1997 and Kőszegi and Rabin 2006). It is worth noting that heuristics also play a major role in Simon's later work, such as Simon (1977). Finally, the decision-theoretic advancements in the last 20 years produced a long sequences of contributions which, starting from a set of behavioral axioms on the DM's preferences, show (via a representation theorem) that these properties imply certain features of the utility function representing preferences (see, e.g., Gilboa and Schmeidler 1993, and Maccheroni et al. 2006).[11]

Indeed, there is no doubt that, by dropping the too rigid assumptions of complete information and perfect computational capacities of economic agents, Simon has opened new patterns of rational behavior, inspired by emerging theories from economics and psychology. Moreover, the relevance of Simon's contribution lies in the variety of insights it offers on the mathematical formalization of behavioral economics. In what follows we analyze some research strands whose genesis takes inspiration from Simon's enlightenments, as summarized in Sect. 4.

5.1 Bounded rationali(zabili)ty in choice

> *The present paper, then, attempts to include explicitly some of the properties of the choosing organism as elements in defining what is meant by rational behavior in specific situations and in selecting a rational behavior in terms of such a definition.*

According to the theory of revealed preferences pioneered by Samuelson (1938), the experimenter observes choice behavior, and then deduces DM's preferences from it. As said in Sect. 3, rationality in choice has originally been encoded *sic et simpliciter* by the technical notion of *rationalizability*, intended as the possibility to interpret the

[10] A similar definition of bounded rationality has been adopted by Selten (see, e.g., Selten 1990).

[11] We thank a referee for suggesting this interesting classification. Note that in this commentary we aim to offer a wide perspective on Simon's legacy, and so we sometimes mention contributions that are not formally adhered to Simon's bounded rationality paradigm, but have however been inspired by the economic assumptions discussed in his paper.

DM's choice as the maximization of the binary relation of revealed preference. For stochastic choices, the generalization of rationalizability due to Block and Marschak (1960) requires the existence of a probability distribution over all the potential DM's preferences (linear orders) such that, for any menu and any alternative, the probability of being selected equals the sum of the probabilities attached to the preferences for which the selected item is the maximal one in that menu. In a nutshell, the following "equivalence" is assumed to hold:

$$\text{rationality} \;\equiv\; \text{rationalizability}. \tag{1}$$

According to this (quite restrictive) interpretation, rationality in choice behavior accounts to choose from all feasible menus in a way that is fully compatible with either a (consistent) selection on pairs of alternatives, or a feasible probability distribution over such binary selections.

However, the process of encoding choice rationality by means of the technical notion of rationalizability exhibits at least two weaknesses. First, it is based on the (very strong) assumption that the economic agent is endowed with full information and computational power, and it does not incorporate any behavioral feature. Second, it does not explain the overwhelming majority of empirical/experimental findings.[12]

Although the notion of standard rationality relevant for Simon is associated with the maximization of expected utility (the probabilistic rule)—but not with the revealed preference approach—his findings have been successfully applied in individual choice theory. Indeed, the enlightening analysis of Simon based on the search for alternative *"reasonable"* decision procedures has given rise—especially during the last twenty years—to several notions of *bounded rationali(zabili)ty*, which aim to explain a larger/distinct portion of behavior by means of more flexible models of choices. This novel codification of rationality employs regularity properties coherent with emerging advances in economics and psychology. In a nutshell, the equivalence (1) has been progressively and consistently substituted by the less demanding equivalence

$$\text{rationality} \;\equiv\; \text{bounded rationali(zabili)ty}. \tag{2}$$

To witness the trend to interpret rationality according to (2), let us mention few (among the many) bounded rationality models in choice that have been introduced in the literature in the recent past, each of which refers to a specific DM's behavioral bias.[13]

For instance, in Manzini and Mariotti (2007) the DM ponders several criteria (asymmetric binary relations) to evaluate feasible alternatives, but he is not able to apply all of them simultaneously. Thus, he chooses from each menu the item that survives after the sequential application of each criterion, in a fixed order. This choice procedure,

[12] See, e.g., Giarlotta et al. (2022) for some related computations.

[13] This trend of analysis has become so important that in 2013 Paola Manzini and Marco Mariotti organized the first meeting of the conference BRIC (Bounded Rationality In Choice), which brings together researchers in choice theory, experimental economics, and behavioral economics who are interested in how bounds on rationality play out in individual decisions and interactive situations. This conference has become an annual event since 2013, and collects an increasing number of attendees.

which is prompted by the computational limits affecting the DM, justifies *cyclical choices*, a pathological behavior documented in many experimental and empirical settings.

A different sequential choice model is proposed by Apesteguia and Ballester (2013). In their work the authors assume that the DM's selection is guided by routes describing the order in which pairs of alternatives in the menu are compared by the DM.

Bordalo et al. (2013) analyze the effect of salience on individual evaluation of alternatives. In their framework, salience is an increasing function of the distance of attributes (payoffs, prices, quality, etc.) from the average, and it distorts the DM's evaluation by inflating the relative utility weights attached to salient attributes of goods. Their approach explains some behavioral anomalies, such as decoy effects and contex-dependent willingness to pay.

Recently, Yegane (2022) analyzes the effects of human limited memory on consumer choice. In this framework the DM observes available alternatives according to a list, but he may forget some of them. When he examines a new item in the list, he recalls the previous options, which have not been already forgotten, with some probability. Eventually, he maximizes a preference relation over the subset of alternatives he recalls after he exhausted the list. This procedure is examined in a monopolist's problem in which consumers suffer of limited memory, and it is shown that the monopolist's profit is higher when the probability of forgetting is high and he charges a lower price.

We believe that, in absence of Simon's pioneering ideas, this fervid stream of research would have not been developed with so much enthusiasm.

5.2 Limited consideration

> *Models of rational behavior [...] generally require some or all of the following elements: [...] The subset of behavior alternatives that the organism "considers" or "perceives". That is, the organism may make its choice within a set of alternatives more limited than the whole range objectively available to it.*

One of the components of Simon's rational model is the set of *"considered"* alternatives. The author states that the DM may not examine some items, thus only considering a subset of the available alternatives. This intuition has been confirmed by many empirical and experimental contributions (see, e.g., Roberts and Lattin 1991). In economic theory, the notion of *limited consideration* has been first formalized by Eliaz and Spiegler (2011), who propose a model of competitive marketing in which boundedly rational consumers do not have a perfect perception of their *consideration set*, i.e., the set of alternatives relevant for their choice, and new alternatives that appear in the market are often not considered. Thus, a firm can use marketing strategies to manipulate consumers considerations sets, and induce them to consider its product. Firms' profits in equilibrium are affected by the fraction in the market of rational consumers, those who perfectly perceive their consideration set.

Limited consideration allows also to justify choices that are not rational according to the canonical definitions analyzed in Sect. 3. Indeed, in their seminal work, Masatlioglu et al. (2012) assume that the DM's attention is limited, and he can observe only some of the available alternatives, as in the model determined by an *attention filter*. The DM finally selects the item that maximizes, among the observed ones, his preference. This approach, later generalized in Cattaneo et al. (2020) in a stochastic environment, explains some frequently observed behavioral phenomena, such as the attraction effect.

Another declination of limited consideration has been offered by Manzini and Mariotti (2014). According to their approach the DM observes each alternative in the menu with a given probability, and then selects the option that maximizes her preference. This procedure allows one to uniquely identify the revealed preference relation and the attention parameters from observed choice data, also accommodating for menu effects and stochastic intransitivity of choices.

Lleras et al. (2017) define a testable property of limited consideration for deterministic choices, which provides a theoretical explanation of the notion of *choice overload*. In fact, in their model, reducing the number of considered alternatives may enhance the DM's welfare, as measured by the preference revealed from choice data.

In Giarlotta et al. (2023) the DM's attention—and the derived consideration sets—are affected only by salient items holding an extreme position in his preference. The authors show that their model of *salient limited attention* is a specification of Masatlioglu et al. (2012), and find numerical estimates that confirm the selectivity of their approach.

Finally, Carpentiere and Petralia (2023) show that many testable choice patterns do have an alternative representation under limited consideration, and describe the properties of the associated consideration set. Moreover, the authors characterize the behavior of *minimal* observers—those who only consider a small amount of alternatives—and retrieve unique consideration sets from their observed choices.

5.3 Satisficing

In psychological theory we would fix the boundary at the "aspiration level"; in economic theory we would fix the boundary at the price which evokes indifference between selling and not selling (an opportunity cost concept).

Among the main intuitions offered by Simon, there is the possibility that the DM may select an alternative whose consequences satisfy a given payoff threshold, the so-called *"aspiration level"* (or *"acceptable price"*). Such a decision process, typically called *satisficing*, may fail to be optimal according to the traditional utility maximization principle, but takes into consideration human computational limits.

Satisficing behavior has been extensively analyzed in experimental economics and economic theory, finally becoming an independent and massive stream of research. Inspired by Simon's analysis, Winter (1971) investigates competitive markets in which firms adopt a satisficing behavior. Specifically, each firm produces net outputs as long as its profit exceeds a given threshold. Under further conditions about the demand function, the firm technology, and decision rules, there exists a competitive equilibrium.

The procedure described by Castagnoli and LiCalzi (2006) ranks real valued acts according to the probability to perform better than a given randomized benchmark of satisfaction. The authors find characterizing properties of DM's preferences over acts that can be represented as benchmarking rules.

The satisficing procedure proposed in Simon (1955) is explicitly mentioned in Papi (2012). In this work the DM sequentially explores several menus, looking for some alternative that is more satisfactory, according to his preference, than a given reference point. If he finds such an alternative, then he selects it, and his search comes to an end. Otherwise, he selects the most preferred unsatisfactory item among the observed ones. The author inspects and characterizes three distinct models, in which the sequence of observed menus are fully observable, partially observable (only the first menu proposed to the DM is known), or unobservable.

Güth (2010) proposes a definition of satisficing choice which accounts for multiple scenarios. An aspiration payoff is associated to each scenario, and a choice is satisfying if it yields a payoff larger than the aspired one in any scenario. Moreover, an experimental test allows to elicit individual preferences, aspirations, and expectations.

In the decision process shaped by Tyson (2021), satisficing behavior is the consequence of the impossibility for the DM to fully discern his true preference. In fact, the DM may rely on *satisficing sets* of alternatives that are undominated according to the perceived preference. This paradigm is adopted to describe a duopolistic market with satisficing consumers. In the case of simultaneous pricing, the ability of firms to set a price greater than the marginal cost is inversely proportional to the ability of consumers to perceive their own preferences. However, if firms sequentially determine their price, then their market shares in equilibrium is independent of the preference resolution parameter.

5.4 Dynamic updating

> *In one organism, dynamic adjustment over a sequence of choices may depend primarily upon adjustments of the aspiration level. In another organism, the adjustments may be primarily in the set* $\mathring{A}$: *if satisfactory alternatives are discovered easily,* $\mathring{A}$ *narrows; if it becomes difficult to find satisfactory alternatives,* $\mathring{A}$ broadens.

To further extend his model, Simon assumes that aspiration levels, preferences, and consideration set may change after the observation of some alternatives. However, the circumstance that aspiration levels are dynamic or endogenous may pose challenging issues, because there is no overall accepted theory of how dynamicity or endogeneity work. At any rate, Simon's setting is the precursor of several contributions that analyze *dynamic updating* of DM's subjective features.

Simultaneously to Simon's paper, Strotz (1955) formalizes for the first time an intertemporal choice problem, in which the DM schedules an optimal consumption plan, given a budget constraint that changes over time. Indeed, several contributions to economic theory have been devoted to define updating processes of the DM's beliefs over the possible states of the world (and, as a consequence, of the DM's choices), on the basis of Bayes' rule.

Gilboa and Schmeidler (1993) question the traditional bayesian approach, which postulates that each economic agents maximize the expected utility generated by a unique prior probability. This critique is supported by experiments showing that individuals tend to violate the consistency conditions underlying the expected utility maximization, and often they are unable to determine a prior in inference problems. Thus, the authors characterize several beliefs updating rules, assuming that the DM is endowed with multiple priors over events, and introduce a class of *pseudo-Bayesian* rules, which generalize Bayes' rule for a unique prior.

Maccheroni et al. (2006) give an axiomatic characterization of *dynamic variational preferences*, which evaluate each act according to the sum of its minimal expected value among all the possible priors, and the cost of choosing the minimizing prior. They generalize the max-min approach of Gilboa and Schmeidler (1989), and offer a microeconomic justification of the *multiplier preferences model* introduced by Hansen and Sargent (2006).

Hanany and Klibanoff (2007) propose update rules for max-min expected utility preferences, which are dynamically consistent and coherent with the characteristic features of behavior under ambiguity. Their approach explains a dynamic version of the three-color Ellsberg's problem, which is not compatible with any theory based on recursion or backward induction, nor coherent with any dynamically consistent update rule.

Yeon-Koo and Mierendorff (2019) assume that before taking an action the DM searches for new sources of information on the occurrence probability of each state of the world. Acquired information affects the DM's prior and his final action. This model is eventually applied to media consumption, showing that the beliefs of agents with extreme political views become more polarized, since they consume own-biased outlets. On the contrary, the beliefs of moderate agents tend to converge toward the middle, since they put increasing attention to opposite media outlets.

5.5 Success and testability

> *Moreover in many situations we may be interested in the precise question of whether one decision-making procedure is more rational than another, and to answer this question we will usually have to construct a broader criterion of rationality that encompasses both procedures as approximations.*

Simon puts forth the idea of comparing models of choice on the basis of their rationality. In theoretical and experimental economics, this suggestion has stimulated several contributions, which aim to verify the *success* of a bounded rationality model, intended as its aptitude to fit choice data.

A seminal approach is due to Selten (1991), who defines the measure of predictive success of a theory as a function of two variables: the *hit rate* (the relative frequency of empirical/experimental correct predictions) and the *theory's area* (the relative size of the subset of all possible outcomes explained by the theory). The efficiency of three versions of such measure is analyzed: (i) the difference between the hit rate and the area, (ii) the ratio between them, and (iii) the ratio between their difference and the complement of the theory's area.

More recently, Oprea (2020) experimentally verifies the DM's adversity to complex choice rules. Subjects face a sequence of rules to implement, and then exhibit their willingness to pay to avoid to implement complex rules. The characteristics that make rules costly for the subject are disentangled; moreover, it is shown that the perceived complexity of the rule is also affected by its framing and the DM's past experience.

Aguiar et al. (2023) perform a large-scale online experiment, which suggests that the random utility model does not explain the population behavior. On the contrary, there is no evidence against the hypothesis that consumers may decide according to stochastic models of limited attention.

The success of a bounded rationality model is closely connected with its *testability*, that is, the propensity of the model to explain a relatively small subset of all possible choice behaviors. The rationale behind this desirable feature is that too permissive theories cannot really identify rational behavior, and so they become useless from an experimental perspective.

The overall testability of several bounded rationality models have been recently explored by Giarlotta et al. (2022). The authors show that many bounded rationality models present in the literature behave as they should, namely the fraction of deterministic choices explained by each model goes to zero as the number of items tends to infinity; moreover, bounded rationality proves to be rare even for relatively small set of alternatives.

A similar analysis has been performed for stochastic choice functions by de Clippel and Rozen (2023), who observe that the fraction of choices explained by RUM and many other stochastic choice theories tends to zero as the size of the ground set diverges.

5.6 Measures of rationality

> *The question of how it is to behave "rationally", given these limitations, is distinct from the question of how its capabilities could be increased to permit action that would be more "rational" judged from the mountain-top of a more complete model.*

Simon mentions the gap between actual choice behavior and choices that can be considered rational, according to models based on complete information and powerful analytic abilities of the DM. This consideration has inspired *measures of rationality*, which aim to evaluate deviations of observed choice data from some standard benchmark of rationality. These measures of rationality have originally been designed for specific fields of research, and successively have been adapted to the general case.

In consumer demand theory, Afriat (1973) introduces a parameter of *cost efficiency* that measures how severely, given a budget constraint, the DM's observed behavior departs from utility maximization. In the same direction Varian (1990) proposes parametric and non-parametric methods to measure the magnitude of deviations from optimal consumption choice.

Echenique et al. (2011) look at the failures of the *general axiom of revealed preference* (*GARP*) in consumers' choices. In their setting, violations of this property are cycles in the DM's preference revealed by the observed consumption bundles. Thus, for each violation of GARP a *money-pump index (MPI)* arises as the sum (across all the pairs of observations that belong to the considered cycle) of the amount of money needed to switch from the chosen bundle to a non-chosen one. This measure has been refined by Dean and Martin (2016), who consider the minimum MPI computed over the complement of some acyclic binary relation contained in the DM's revealed preference.

Several works discuss rationality of choice behavior, either deterministic or stochastic. In the multi-self approach of Kalai et al. (2002), the DM has multiple preferences (linear orders), and she selects from each menu the unique element that is maximal according to one (any) of these rationales. The *degree of rationality* of a deterministic choice behavior is then defined as the minimum number of linear orders needed to explain the selection process. This generates a partition of all choice functions on n elements into $n-1$ classes of rationality, where the least rational class asymptotically collects all behaviors.

A context-sensitive refinement of this index is discussed in Giarlotta et al. (2023), who require that the preference justifying the DM's selection must be indexed by a maximally salient item in the menu. The generated partition distinguishes n classes of rationality, where again the last class eventually collects almost all behaviors. An additional approach based on counting procedures is due to Caradonna (2020), who measures irrationality of choice correspondences through observed revealed preference cycles.

In a different direction, Carpentiere et al. (2023) determine the degree of irrationality of a deterministic choice behavior as follows: (i) select a benchmark of rationality, (ii) endow the set of choices with a highly discerning metric, and (iii) measure deviations from rationality by computing the minimum distance from the benchmark. Here rationalizable choices constitute the benchmark of rationality, and a sharpening of Klamler (2008)'s distance is the metric that measure deviations.[14]

The revolution of bounded rationality inspired by Simon has very recently fostered approaches to measure the rationality of stochastic choice behavior. Apesteguia and Ballester (2015) count the *swaps* of a stochastic choice: they compute the sum, across all menus, of the number of alternatives that must be swapped with the chosen one to obtain a (deterministic) choice function rationalizable by some linear order on the ground set.Thus, they define the *swap index* as the minimal sum of swaps that can be obtained from choice data considering all the possible linear orders on the set of alternatives.

A different approach to determine the level of rationality of a stochastic choice behavior is due to Ok and Tserenjigmid (2021). Using Fishburn (1978)'s families of deterministic choice correspondences associated to any stochastic behavior, the authors obtain a partial order on the collection of stochastic choice functions, where incomparability plays a major role.

A possibly incomplete preorder of rationality is also obtained by Carpentiere et al. (2023), who take the random utility model (Block and Marschak 1960) as a benchmark of rationality, and then use Block-Marschack polynomials—whose non-negativity characterize random utility models, according to Falmagne (1978)—to classify stochastic choice behaviors according to their level of (ir)rationality.

[14] A correct characterization of Klamler's distance is discussed in Carpentiere et al. (2023).

6 Concluding remarks

The scientific resonance of Simon (1955)'s work is attested by the vast amount of citations and related publications. However, even more important is the epistemic value of the research. The following two final considerations exemplify the impact of Simon's theoretical contribution.

First, the idea of introducing behavioral features into theoretical choice patterns has triggered the emergence of several bounded rationality models, which describe empirical rules and anomalies not explicitly discussed by Simon, such as the *avoidance of the handicapped* (Snyder et al. 1979), the *attraction effect* (Simonson 1989), and the *compromise effect* (Kivetz et al. 2004).

Second, insights offered by Simon's seminal paper raise scientific questions, which are still open as of today. For instance, even if the topic has been recently explored (Sawa and Zusai 2014), *dynamic aspiration levels* and information gathering in choice have not been characterized yet, nor parametrically identified. Similarly, Simon's suggestion about the opportunity to model the DM's *dynamic attention* has not been fully implemented in economic theory, although there are some recent contributions in this direction (Maćkowiak et al. 2018).

We hope that this note may foster scholars to attentively explore Simon's contributions, and possibly fill some of the gaps in the current state of art on bounded rationality.

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