Mohammed Abdellaoui
John D. Hey
Editors

SERIES C: Game Theory, Mathematical Programming and Operations Research 42

Advances in Decision Making Under Risk and Uncertainty

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VOLUME 42

Scope: Particular attention is paid in this series to game theory and operations research, their formal aspects and their applications to economic, political and social sciences as well as to sociobiology. It will encourage high standards in the application of game-theoretical methods to individual and social decision making.

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Preface

This volume contains a selection consisting of the best papers presented at the FUR XII conference, held at LUISS in Roma, Italy, in June 2006, organized by John Hey and Daniela Di Cagno. The objectives of the FUR (Foundations of Utility and Risk theory) conferences have always been to bring together leading academics from Economics, Psychology, Statistics, Operations Research, Finance, Applied Mathematics, and other disciplines, to address the issues of decision-making from a genuinely multi-disciplinary point of view. This twelfth conference in the series was no exception. The early FUR conferences – like FUR I (organized by Maurice Allais and Ole Hagen) and FUR III (organized by Bertrand Munier) – initiated the move away from the excessively rigid and descriptively-inadequate modelling of behaviour under risk and uncertainty that was in vogue in conventional economics at that time. More than twenty years later, things have changed fundamentally, and now innovations arising from the FUR conferences, and manifesting themselves in the new behavioural economics, are readily accepted by the profession. Working with new models of ambiguity, and bounded rationality, for example, behavioural decision making is no longer considered a sign of mere non-standard intellectual diversification. FUR XII was organised with this new spirit. In the sense that the behavioural concerns initiated by the first FUR conferences are now part of conventional economics, and the design and organisation of FUR XII reflects this integration, FUR XII represents a key turning point in the FUR conference series.

The 13 papers in this volume represent a sample of the best recent work in normative and descriptive modelling of behaviour under risk and uncertainty. We have divided the 13 papers into four broad parts (although there are obvious overlaps between the various parts): Uncertainty and information modelling; Risk modelling; Experimental individual decision making; and Experimental Interactive decision making.

Part I: Uncertainty and Information Modelling

There are four papers in this section. The one by Ghirardato et al. makes the fundamental claim that dynamic consistency – the fundamental property in dynamic choice models – is only compelling for choice situations in which acts are not affected by the possible presence of ambiguity. Their approach is based on one of the most general representations of preferences under uncertainty available up to now in the literature. Needless to say, such an approach opens new avenues of research on ambiguity. It also gives an edifying example of the maturity of research on decision making under uncertainty reached when FUR XII was organised.

Cohen et al. are also concerned with dynamic decision making under uncertainty but with exogenously given probabilities; they are interested in the role of risk perception. Their paper is another example of the use of insights from psychology and behavioural decision making in preference modelling.

Using a general framework of conditional preferences under uncertainty in the context of sequential equilibrium and rationalisability (building on earlier work by Asheim and Perea), Asheim shows that a conditional probability system (where each conditional belief is a subjective probability distribution) may lead to a refinement of a preference between two acts when new information – ruling out states at which the two acts coincide – becomes available.

Assuming that individual choice behaviour depends on more than the alternatives the decision maker is objectively facing, Stecher proposes an original axiomatic setup in which agents have preferences on their private subjective conceptions of possible alternatives. Given this axiomatic structure, the author provides conditions under which agents can communicate with others who do not necessarily perceive the world in the same way. The paper concludes that successful coordination needs the communication language between agents (for trade purposes) to be sufficiently vague. This is an important, if counter-intuitive, conclusion.

Part II: Risk Modelling

There are just three papers in this section. The first, one by Borgonovo and Peccati, works within the expected utility framework. They tackle sensitivity analysis as an integral part of any decision making process. Specifically, the authors answer two questions: the first concerning the response of decision making problems to small changes in the input (parameters); and the second relating to the problem of how the change is apportioned to input variations. The answers are important and interesting.

The second paper in the section is by Kaivanto and addresses the question of whether Cumulative Prospect Theory (CPT) resolves the famous St. Petersburg Paradox. Building on Rabin's "law of small numbers" (Rabin 2002), the author shows that the apparent failure of CPT popular parameterizations to resolve the paradox can be explained by the alternation bias inherent to the coin tossing process in the St. Petersburg gamble.

The final paper, one by Fabiyi, raises an interesting issue with respect to the form of the weighting function used in (Cumulative) Prospect Theory and in Rank Dependent Expected Utility function. Empirically it has often been observed to be S-shaped. Fabiyi provides a normative basis for this empirical finding.

Part III: Experimental Individual Decision Making

There are four papers in this section, illustrating the importance of experimental work and the amount of activity in this sector. The first is by Neugebauer who reports on an experiment in which the subject has to allocate his or her investment capital towards three assets. The experimental results confirm two main findings in behavioural decision making and behavioural finance – that is, first, that most subjects choose a dominated lottery when dominance is not transparent and, second, that subjects are loss-averse rather than variance-averse.

Carbone's contribution is concerned with the issue of dynamic inconsistencies and explores the possible influence of temptation as a reason for such inconsistencies. Motivated by the literature on hyperbolic discounting, she uses an innovative experimental design to investigate whether subjects are affected by temptation. The design involves an experiment with two treatments – one a 'spot market' and the other a 'forward market' – which should detect the existence of hyperbolicity. Interestingly, she finds little evidence of such behaviour.

Morone and Fiore report on an experiment in which the famous Monty Hall's three doors anomaly "should" go away. They deliberately adopt a design (Monty Hall's Three Doors for Dummies") which does not rely on subjects being able to do Bayesian updating. Nevertheless the anomaly does not go away – suggesting that the reasons for the anomaly are deeper and different than previously thought.

Giardini et al. argue, on the basis of two experimental studies using a 'visual motion discrimination task', that the desirability of an outcome may bias the amount of confidence people assign to the likelihood of that outcome. The originality of the authors' results lies in their observation that the correlation between reward and confidence was not linked to change in accuracy. In other words, subjects were not more accurate in responding to the stimulus; they were just more confident in their performance when facing a higher reward.

Part IV: Experimental Interactive Decision Making

The final section (on interactive experiments) contains three studies. That by Eichberger et al. extends the experimental study of ambiguity from individual decision making to interactive decision making (that is, to strategic games). The authors consider a non-standard situation in which players lack confidence in their equilibrium conjectures about opponents' play. They use "grannies, game theorists and fellow subjects" to introduce different levels of ambiguity in strategic games, and test comparative static propositions relating to changes in equilibrium with respect to changes in ambiguity.

Morone and Morone address the topic of guessing games with the objective of understanding whether people play in a rational or naïve way. They first develop a generalised theory of naïveté (that generalises the iterative naïve best replies strategy), and experimentally compare the iterative best replies strategy with the iterative elimination of dominated strategies for the generalised p-beauty contest.

Di Cagno and Sciubba explore network formation in a laboratory experiment. Instead of focusing on the traditional issue of convergence to a stable-network architecture, the authors use a network formation protocol suggesting that links are not unilateral, but have to be mutually agreed upon in order to form. The experimental results are analyzed from both ‘macro’ and ‘micro’ perspectives.

Taken together, the papers in this volume, a small subset of the papers presented at the 2006 FUR conference, show well what FUR is and what it does. We have already commented on the diversity of the papers in this volume, but the volume shows another facet of FUR – the desire and the ability to explore, both theoretically and empirically, new models of human behaviour. More importantly, as a study of the development of FUR over the years shows clearly, this volume manifests the clear and strong relationship between the theoretical and empirical developments: many of the empirical contributions would not have been possible without the earlier theoretical developments, and many of the theoretical papers are motivated by a desire to explain interesting phenomena thrown up by previous empirical papers. FUR demonstrates a strong commitment to interaction between theory and empirics. The editors of the present volume and the conference organizers are proud to contribute to keeping the FUR tradition alive.

Mohammed Abdellaoui
Jouy en Josas, April 2008
John D. Hey
York, April 2008

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Part I
Uncertainty and Information Modeling

Revealed Ambiguity and Its Consequences: Updating

P. Ghirardato(✉), F. Maccheroni, and M. Marinacci

Keywords: Ambiguity · Updating

1 Introduction

Dynamic consistency is a fundamental property in dynamic choice models. It requires that if a decision maker plans to take some action at some juncture in the future, he should consistently take that action when finding himself at that juncture, and vice versa if he plans to take a certain action at a certain juncture, he should take that plan in mind when deciding what to do now.

However compelling *prima facie*, it is well known in the literature that there are instances in which the presence of ambiguity might lead to behavior that reasonably violates dynamic consistency, as the next Ellsberg example shows.[1]

Example 1. Consider the classical "3-color" Ellsberg problem, in which an urn contains 90 balls, 30 of which are known to be red, while the remaining 60 are either blue or green. In period 0, the decision maker only has the information described above. Suppose that at the beginning of period 1 a ball is extracted from the urn, and the decision maker is then told whether the ball is blue or not. The decision maker has to choose between bets on the color of the drawn ball. Denoting by $[a,b,c]$ an act that pays a when a red ball is extracted, b when a green ball is extracted and c otherwise, let

$$f = [1,0,0]$$
$$g = [0,1,0]$$

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$$f' = [1,0,1]$$
$$g' = [0,1,1]$$

Suppose that in period 0, the decision maker, like most people in Ellsberg's experiment, displays the following preference pattern

$$g' \succ f' \succ f \succ g \tag{1}$$

(the middle preference being due to monotonicity). Letting $A = \{R, G\}$, it follows immediately from consequentialism that, conditionally on A^c,

$$f' \sim_{A^c} g'.$$

On the other hand, if the decision maker's conditional preferences satisfy dynamic consistency it must be the case that if he finds an act to be optimal conditionally on A and also conditionally on A^c in period 1, he must find the same act optimal in period 0. So, dynamic consistency implies that $g' \succ_A f'$ (as otherwise we should have $f' \succcurlyeq g'$). That is, a dynamically consistent and consequentialist decision maker who is told that a blue ball has not been extracted from the Ellsberg urn (i.e., is told A) must strictly prefer to bet on a green ball having been extracted.

Yet, it seems to us that a decision maker with the ambiguity averse preferences in (1) *might* still prefer to bet on a red ball being extracted, finding that event less ambiguous than the extraction of a green ball, and that constraining him to choose otherwise is imposing a strong constraint on the dynamics of his ambiguity attitude.

In view of this example, we claim that dynamic consistency is a compelling property only for comparisons of acts that are not affected by the possible presence of ambiguity. In other words, we think that rankings of acts unaffected by ambiguity should be dynamically consistent.

This is the starting point of this paper. We consider the preferences represented by

$$V(f) = a(f)\min_{P\in C}\int u(f(s))\,dP + (1-a(f))\max_{P\in C}\int u(f(s))\,dP, \tag{2}$$

where f is an act, a is a function over acts that describes the decision maker's attitudes toward ambiguity, and C is a set of priors that represents the ambiguity revealed by the decision maker's behavior. We provided an axiomatic foundation for such preferences in Ghirardato et al. (2004, henceforth GMM).[2] There, we also introduced a notion of unambiguous preference which is derived from the observable preference over acts. We argued that such derived unambiguous preference only ranks pairs of acts whose comparison is not affected by ambiguity. That is, unambiguous preference is a partial ordering, which is represented *à la* Bewley (2002) by the set of priors C (see (3) below).

Our main intuition is then naturally modelled by assuming that the derived unambiguous preference is dynamically consistent, while, in the presence of ambiguity, the primitive preference might well not be. This natural modelling idea leads to a simple and clean characterization of updating for the preferences we discuss in GMM. The main result of the present paper, Theorem 1, shows that the unambiguous preference is dynamically consistent if and only if all priors in C are updated according to Bayes' rule. This result thus characterizes prior by prior Bayesian updating, a natural updating rule for the preferences represented by (2).

We also consider a stronger dynamic consistency restriction on preferences, which can be loosely described as imposing dynamic consistency of the decision maker's "pessimistic self." We show that such restriction (unlike the one considered earlier) leads to imposing some structure on the decision maker's ex ante perception of ambiguity, which corresponds to the property that Epstein and Schneider (2003) have called *rectangularity*. This shows, *inter alia*, that rectangularity is not in general (i.e., for the preferences axiomatized in GMM) the characterization of dynamic consistency of the primitive preference relation, but of a different dynamic property which might even be logically unrelated to it.

We close by observing that we retain consequentialism of the primitive preference, another classic dynamic property that requires that preferences conditional on some event A only depend on the consequences inside A. This property has been weakened in Hanany and Klibanoff (2004), which also offers a survey of the literature on dynamic choice under ambiguity.

2 Preliminaries

2.1 Notation

Consider a set S of **states of the world**, an algebra Σ of subsets of S called **events**, and a set X of **consequences**. We denote by $\mathfrak{F}$ the set of all the **simple acts**: finite-valued Σ-measurable functions $f : S \to X$. Given any $x \in X$, we abuse notation by denoting $x \in \mathfrak{F}$ the constant act such that $x(s) = x$ for all $s \in S$, thus identifying X with the subset of the constant acts in $\mathfrak{F}$. Given $f, g \in \mathfrak{F}$ and $A \in \Sigma$, we denote by fAg the act in $\mathfrak{F}$ which yields $f(s)$ for $s \in A$ and $g(s)$ for $s \in A^c \equiv S \setminus A$. We model the DM's preferences on $\mathfrak{F}$ by a binary relation $\succcurlyeq$. As usual, $\succ$ and $\sim$ denote respectively the asymmetric and symmetric parts of $\succcurlyeq$.

We let $B_0(\Sigma)$ denote the set of all real-valued Σ-measurable simple functions, or equivalently the vector space generated by the indicator functions 1_A of the events $A \in \Sigma$. If $f \in \mathfrak{F}$ and $u : X \to \mathbb{R}$, we denote by $u(f)$ the element of $B_0(\Sigma)$ defined by $u(f)(s) = u(f(s))$ for all $s \in S$. A *probability charge* on (S, Σ) is function $P : \Sigma \to [0,1]$ that is normalized and (finitely) additive; i.e., $P(A \cup B) = P(A) + P(B)$ for any disjoint $A, B \in \Sigma$. Abusing our notation we sometimes use $P(\varphi)$ in place of $\int \varphi \, dP$, where $\varphi \in B_0(\Sigma)$.

Given a functional $I : B_0(\Sigma) \to \mathbb{R}$, we say that I is: **monotonic** if $I(\varphi) \geq I(\psi)$ for all $\varphi, \psi \in B_0(\Sigma)$ such that $\varphi(s) \geq \psi(s)$ for all $s \in S$; **constant additive** if $I(\varphi + \alpha) = I(\varphi) + \alpha$ for all $\varphi \in B_0(\Sigma)$ and $\alpha \in \mathbb{R}$; **positively homogeneous** if $I(\alpha\varphi) = \alpha I(\varphi)$ for all $\varphi \in B_0(\Sigma)$ and $\alpha \geq 0$; **constant linear** if it is constant additive and positively homogeneous.

Finally, as customary, given $f \in \mathfrak{F}$, we denote by $\Sigma(f)$ the algebra generated by f.

2.2 Invariant Biseparable Preferences

We next present the preference model used in the paper. We recall first the MEU model of Gilboa and Schmeidler (1989). In this model, a decision maker is represented by a utility function u and a set of probability charges $\mathcal{C}$, and she chooses according to the rule $\min_{P \in \mathcal{C}} \int u(\cdot)\, dP$. A generalization of this model is the so-called **α-maxmin** (α-MEU) model, in which the decision maker evaluates act $f \in \mathfrak{F}$ according to

$$\alpha \min_{P \in \mathcal{C}} \int_S u(f(s))\, dP(s) + (1-\alpha) \max_{P \in \mathcal{C}} \int_S u(f(s))\, dP(s).$$

The α-MEU model is also a generalization – to an arbitrary set of priors, rather than the set of all possible priors on Σ – of Hurwicz's *α-pessimism* decision rule, which recommends evaluating an act by taking a convex combination (with weight α) of the utility of its worst possible result and of the utility of its best possible result. In collaboration with Arrow and Hurwicz (1972), Hurwicz later studied a generalization of his rule, which allows the "pessimism" weight α to vary according to the identity of the worst and best results that the act may yield.

As it turns out, there is a similar generalization of the α-MEU model allowing the weight α to depend on some features of the act f being evaluated. It is the model studied by GMM (see also Nehring (2001) and Ghirardato, Maccheroni, Marinacci, and Siniscalchi (2003)), which relaxes Gilboa and Schmeidler's axiomatization of MEU by not imposing their "ambiguity aversion" axiom (and is constructed in a fully subjective setting). We present its functional characterization below, referring the reader to the cited Ghirardato et al. (2003, 2004) for the axiomatic foundation and further discussion. (The axioms are simply those of Gilboa and Schmeidler (1989) minus their "uncertainty aversion" axiom.)

Definition 1. A binary relation $\succcurlyeq$ on $\mathfrak{F}$ is called an **invariant biseparable preference** if there exist a unique monotonic and constant linear functional $I : B_0(\Sigma) \to \mathbb{R}$ and a nonconstant convex-ranged utility $u : X \to \mathbb{R}$, unique up to a positive affine transformation, such that $I(u(\cdot))$ represents $\succcurlyeq$; that is, for every $f, g \in \mathfrak{F}$,

$$f \succcurlyeq g \Leftrightarrow I(u(f)) \geq I(u(g)).$$

It is easy to see (see GMM, p. 157) that a functional $I : B_0(\Sigma) \to \mathbb{R}$ that satisfies monotonicity and constant linearity is also *Lipschitz continuous* of rank 1; i.e., $|I(\varphi) - I(\psi)| \leq \|\varphi - \psi\|$ for any $\varphi, \psi \in B_0(\Sigma)$.

In order to show how this model relates to the α-MEU model, we need to show how to derive a set of priors and consequently the decision maker's ambiguity attitude.

Suppose that act f is preferred to act g. If there is ambiguity about the state space, it is possible that such preference may not hold when we consider acts which average the payoffs of f and g with those of a common act h. Precisely, it is possible that a "mixed" act $g \lambda h$, which in each state s provides the average utility

$$u(g\lambda h)(s) = \lambda u(g(s)) + (1-\lambda)u(h(s)),$$

be preferred to a "mixed" act $f \lambda h$, which offers an analogous average of the payoffs of f and h. Such would be the case, for instance, if $g \lambda h$ has a utility profile which is almost independent of the realized state – while $f \lambda h$ does not – and the decision maker is pessimistic. On the other hand, there might be pairs of acts for which these "utility smoothing effects" are second-order. In such a case, we have "unambiguous preference." Precisely,

Definition 2. Let $f, g \in \mathfrak{F}$. Then, f is **unambiguously preferred** to g, denoted $f \succcurlyeq^* g$, if

$$f \lambda h \succcurlyeq g \lambda h$$

for all $\lambda \in (0,1]$ and all $h \in \mathcal{F}$.

Notice that in general $\succcurlyeq^*$ is a (possibly incomplete) coarsening of $\succcurlyeq$, while on the other hand for any $x, y \in X$, $x \succcurlyeq^* y$ if and only if $x \succcurlyeq y$.

In GMM we show that given an invariant biseparable preference there exists a unique nonempty, convex and (weak*) closed set $\mathcal{C}$ of probability charges that represents the unambiguous preference relation $\succcurlyeq^*$ in the following sense

$$f \succcurlyeq^* g \Longleftrightarrow \int_S u(f(s))\, dP(s) \geq \int_S u(g(s))\, dP(s) \qquad \text{for all } P \in \mathcal{C}. \tag{3}$$

That is, unambiguous preference corresponds to preference according to every one of the possible "probabilistic scenarios" included in $\mathcal{C}$. The set $\mathcal{C}$ therefore represents the ambiguity that is revealed by the decision maker's behavior.

Given the representation $\mathcal{C}$, the decision maker's index of ambiguity aversion a is then extracted from the functional I in the following natural way:

$$I(u(f)) = a(f) \min_{P \in \mathcal{C}} \int_S u(f(s))\, dP(s) + (1 - a(f)) \max_{P \in \mathcal{C}} \int_S u(f(s))\, dP(s).$$

The coefficient $a : \mathfrak{F} \to [0,1]$ is uniquely identified (GMM, Theorem 11) on the set of acts whose expectation is nonconstant over $\mathcal{C}$; i.e., those f for which it is *not* the case that

$$\int_S u(f(s))\, dP(s) = \int_S u(f(s))\, dQ(s) \text{ for every } P, Q \in \mathcal{C}. \tag{4}$$

Moreover, wherever uniquely defined, a also displays a significant regularity, as it turns out that $a(f) = a(g)$ whenever f and g "order" identically the possible scenarios in $\mathcal{C}$. Formally, for all $P, Q \in \mathcal{C}$,

$$\int_S u(f(s))\,dP(s) \geq \int_S u(f(s))\,dQ(s) \Longleftrightarrow \int_S u(g(s))\,dP(s) \geq \int_S u(g(s))\,dQ(s). \quad (5)$$

(See GMM, Proposition 10 and Lemma 8 respectively, for behavioral equivalents of the above conditions.) In words, the decision maker's degree of pessimism, though possibly variable, will not vary across acts which are symmetrically affected by ambiguity. Notice that in our environment the Arrow–Hurwicz rule corresponds to the case in which a decision maker's degree of pessimism only depends on the probabilities that maximize and minimize an act's evaluation. Thus, letting the degree of pessimism depend on all the ordering on $\mathcal{C}$ is a generalization of the Arrow–Hurwicz rule. Clearly, the SEU model corresponds to the special case in which $\mathcal{C}$ is a singleton. Thus, all SEU preferences whose utility is convex-ranged are invariant biseparable preferences. Less obviously, also CEU preferences with convex-ranged utility are invariant biseparable preferences. Hence, this model includes both α-MEU and CEU as special cases.

Unless otherwise noted, for the remainder of the paper preferences are always (but often tacitly) assumed to be invariant biseparable in the sense just described.

3 Some Derived Concepts

We introduce three notions which can be derived from the primitive preference relation via the unambiguous preference relation. Besides being intrinsically interesting, such notions prove useful in presenting the main ideas of the paper.

3.1 Mixture Certainty Equivalents

For any act $f \in \mathfrak{F}$, denote by $C^*(f)$ the set of the consequences that are "indifferent" to f in the following sense:

$$C^*(f) \equiv \{x \in X : \text{ for all } y \in X,\ y \succcurlyeq^* f \text{ implies } y \succcurlyeq^* x,\ f \succcurlyeq^* y \text{ implies } x \succcurlyeq^* y\}.$$

Intuitively, these are the constants that correspond to possible certainty equivalents of f. The set $C^*(f)$ can be characterized (GMM, Proposition 18) in terms of the set of expected utilities associated with $\mathcal{C}$:

Proposition 1. *For every $f \in \mathfrak{F}$,*

$$x \in C^*(f) \Longleftrightarrow \min_{P \in \mathcal{C}} P(u(f)) \leq u(x) \leq \max_{P \in \mathcal{C}} P(u(f)).$$

Moreover, $u(C^*(f)) = [\min_{P\in\mathcal{C}} P(u(f)), \max_{P\in\mathcal{C}} P(u(f))]$.

It follows immediately from the proposition that $x \in C^*(f)$ if and only if there is a $P \in \mathcal{C}$ such that $u(x) = P(u(f))$. That is, $u(C^*(f))$ is the range of the mapping that associates each prior $P \in \mathcal{C}$ with the expected utility $P(u(f))$.

There is another sense in which the elements of $C^*(f)$ are generalized certainty equivalents of f. Consider a consequence $x \in X$ that can be substituted to f as a "payoff" in a given mixture. That is, such that for some $\lambda \in (0,1]$ and $h \in \mathfrak{F}$,

$$x\lambda h \sim f\lambda h.$$

The following result shows that, while not all the elements of the set $C^*(f)$ can in general be expressed in this fashion, each of them is infinitesimally close (in terms of preference) to a consequence with this property.[3]

Proposition 2. *For every* $f \in \mathfrak{F}$, $C^*(f)$ *is the preference closure of the set*

$$\{x \in X : \exists\lambda \in (0,1], \exists h \in \mathfrak{F} \text{ such that } x\lambda h \sim f\lambda h\}.$$

In light of this result, we abuse terminology somewhat and call $x \in C^*(f)$ a **mixture certainty equivalent** of f, and $C^*(f)$ the **mixture certainty equivalents set** of f.

3.2 Lower and Upper Envelope Preferences

Given the unambiguous preference $\succsim^*$ induced by $\succsim$, we can also define the following two relations:

Definition 3. The **lower envelope preference** is the binary relation $\succsim^\downarrow$ on $\mathfrak{F}$ defined as follows: for all $f,g \in \mathfrak{F}$,

$$f \succsim^\downarrow g \iff \{x \in X : f \succsim^* x\} \supseteq \{x \in X : g \succsim^* x\}.$$

The **upper envelope preference** is the binary relation $\succsim^\uparrow$ on $\mathfrak{F}$ defined as follows: for all $f,g \in \mathfrak{F}$,

$$f \succsim^\uparrow g \iff \{x \in X : x \succsim^* f\} \subseteq \{x \in X : x \succsim^* g\}.$$

The relation $\succsim^\downarrow$ describes a "pessimistic" evaluation rule, while $\succsim^\uparrow$ an "optimistic" evaluation rule. To see this, notice that $\succsim^\downarrow$ ranks acts by the size of the set of consequences that are unambiguously worse than f. In fact, it ranks f exactly as the most valuable consequence that is unambiguously worse than f. The twin relation $\succsim^\uparrow$ does the opposite. We denote by $\succ^\downarrow$ and $\sim^\downarrow$ (resp. $\succ^\uparrow$ and $\sim^\uparrow$) the asymmetric and symmetric components of $\succsim^\downarrow$ (resp. $\succsim^\uparrow$) respectively.

This is further clarified by the following result, which shows that the envelope relations can be represented in terms of the set $\mathcal{C}$ derived in the previous section.

Proposition 3. *For every $f, g \in \mathfrak{F}$, the following statements are equivalent:*

(i) $f \succcurlyeq^{\downarrow} g$ *(resp.* $f \succcurlyeq^{\uparrow} g$*).*
(ii) $\min_{P \in \mathcal{C}} P(u(f)) \geq \min_{P \in \mathcal{C}} P(u(g))$ *(resp.* $\max_{P \in \mathcal{C}} P(u(f)) \geq \max_{P \in \mathcal{C}} P(u(g))$*).*

It follows from this result that $\succcurlyeq^{\downarrow}$ is a 1-MEU preference, in particular an invariant biseparable preference, and that $(\succcurlyeq^{\downarrow})^*$ is represented by $\mathcal{C}$. Moreover, while $\succcurlyeq$ and $\succcurlyeq^{\downarrow}$ always coincide on X, they coincide on $\mathfrak{F}$ if and only if $\succcurlyeq$ is 1-MEU, so that $\succcurlyeq$ and $\succcurlyeq^{\downarrow}$ will be in general distinct. Symmetric observations hold for $\succcurlyeq^{\uparrow}$.

The relations between $\succcurlyeq^{\downarrow}$, $\succcurlyeq^{\uparrow}$ and $\succcurlyeq$ can be better understood by recalling the relative ambiguity aversion ranking of Ghirardato and Marinacci (2002).

Proposition 4. *The preference relation $\succcurlyeq^{\downarrow}$ is more ambiguity averse than $\succcurlyeq$, which is in turn more ambiguity averse than $\succcurlyeq^{\uparrow}$.*

Therefore, the envelope relations can be interpreted as the "ambiguity averse side" and the "ambiguity loving side" of the DM. Indeed, $\succcurlyeq^{\downarrow}$ is ambiguity averse in the absolute sense of Ghirardato and Marinacci (2002), while $\succcurlyeq^{\uparrow}$ is ambiguity loving.

4 Revealed Ambiguity and Updating

Suppose that our DM has an information structure given by some subclass Π of Σ (say, a partition or a sub-algebra), and assume that we can observe our DM's ex ante preference on $\mathfrak{F}$, denoted interchangeably $\succcurlyeq$ or $\succcurlyeq_S$, and his preference on $\mathfrak{F}$ after having been informed that an event $A \in \Pi$ obtained, denoted $\succcurlyeq_A$. For each $A \in \Pi' \equiv \Pi \cup S$, the preference $\succcurlyeq_A$ is assumed to be invariant biseparable, and the utility representing $\succcurlyeq_A$ is denoted by u_A. Clearly, a conditional preference $\succcurlyeq_A$ also induces an unambiguous preference relation $\succcurlyeq_A^*$, as well as mixture certainty equivalents sets $C_A^*(\cdot)$ and a lower envelope preference relation $\succcurlyeq_A^{\downarrow}$. Because $\succcurlyeq_A$ is invariant biseparable, it is possible to represent $\succcurlyeq_A^*$ in the sense of (3) by a nonempty, weak* compact and convex set of probability measures $\mathcal{C}_A$.

We are interested in preferences conditional on events which are (ex ante) unambiguously non-null in the following sense:

Definition 4. We say that $A \in \Sigma$ is **unambiguously non-null** if $xAy \succ^{\downarrow} y$ for some (all) $x \succ y$.

That is, an event is unambiguously non-null if betting on A is unambiguously better than getting the loss payoff y for sure (notice that this is stronger than the definition of non-null event in Ghirardato and Marinacci (2001), which just requires that $xAy \succ y$). This property is equivalently restated in terms of the possible scenarios $\mathcal{C}$ as follows: $P(A) > 0$ for all $P \in \mathcal{C}$.

We next assume that conditional on being informed of A, the DM only cares about an act's results on A, a natural assumption that we call **consequentialism**: For every $A \in \Pi$, $f \sim_A fAg$ for every $f, g \in \mathfrak{F}$. Consequentialism extends immediately to the unambiguous and lower envelope preference relations, as the following result shows:

Lemma 1. *For every $A \in \Pi$, the following statements are equivalent*[4]*:*

(i) $f \sim_A f\ \ A g$ *for every* $f, g \in \mathfrak{F}$.
(ii) $f \sim_A^* f\ \ A g$ *for every* $f, g \in \mathfrak{F}$.
(iii) $f \sim_A^{\downarrow} f\ \ A g$ *for every* $f, g \in \mathfrak{F}$.

For the remainder of this section we tacitly assume that all the preferences $\succcurlyeq_A$ are invariant biseparable and consequentialist.

An important property linking ex ante and ex post preferences is **dynamic consistency**: For all $A \in \Pi$ and all $f, g \in \mathfrak{F}$,

$$f \succcurlyeq_A g \Longleftrightarrow f A g \succcurlyeq g. \tag{6}$$

This property imposes two requirements. The first says that the DM should consistently carry out plans made ex ante. The second says that information is valuable to the DM, in the sense that postponing her choice to after knowing whether an event obtained does not make her worse off (see Ghirardato (2002) for a more detailed discussion).

As announced in Sect. 1, we now inquire the effect of requiring dynamic consistency only in the absence of ambiguity; i.e., requiring (6) with $\succcurlyeq$ and $\succcurlyeq_A$ replaced by the unambiguous preference relations $\succcurlyeq^*$ and $\succcurlyeq_A^*$ respectively. We show that (for a preference satisfying consequentialism) this is tantamount to assuming that the DM updates all the priors in $\mathcal{C}$, a procedure that we call **generalized Bayesian updating**: For every $A \in \Pi$, the "updated" perception of ambiguity is equal to

$$\mathcal{C}|A \equiv \overline{co}^{w^*}\{P_A : P \in \mathcal{C}\},$$

where P_A denotes the posterior of P conditional on A, and $\overline{co}^{w^*}$ stands for the weak* closure of the convex hull.

Theorem 1. *Suppose that $A \in \Pi$ is unambiguously non-null. Then the following statements are equivalent:*

(i) *For every* $f, g \in \mathfrak{F}$,

$$f \succcurlyeq_A^* g \Longleftrightarrow P_A(u(f)) \geq P_A(u(g)) \text{ for all } P \in \mathcal{C}. \tag{7}$$

Equivalently, $\mathcal{C}_A = \mathcal{C}|A$ *and* $u_A = u$.

(ii) *The relation $\succcurlyeq^*$ is dynamically consistent with respect to A. That is, for every* $f, g \in \mathfrak{F}$*:*

$$f \succcurlyeq_A^* g \Longleftrightarrow f A g \succcurlyeq^* g. \tag{8}$$

(iii) *For every* $x, x' \in X$, $x \succcurlyeq x' \Rightarrow x \succcurlyeq_A x'$. *For every* $f \in \mathfrak{F}$ *and* $x \in X$*:*

$$x \in C_A^*(f) \Longleftrightarrow x \in C^*(f A x). \tag{9}$$

(iv) *For every* $f \in \mathfrak{F}$ *and* $x \in X$*:*

$$f \succcurlyeq_A^{\downarrow} x \Longleftrightarrow f A x \succcurlyeq^{\downarrow} x. \tag{10}$$

Alongside the promised equivalence with dynamic consistency of unambiguous preference, this results presents two other characterizations of generalized Bayesian updating. They are inspired by a result of Pires (2002), who shows that when the primitive preference relations $\succcurlyeq_A$ are 1-MEU, generalized Bayesian updating is characterized by (a condition equivalent to)

$$f \succcurlyeq_A (\sim_A) x \Longleftrightarrow fAx \succcurlyeq (\sim) x \tag{11}$$

for all $f \in \mathfrak{F}$ and $x \in X$. Statement (iii) in the proposition departs from the indifference part of (11) and applies its logic to the "indifference" notion that is generated by the incomplete preference $\succcurlyeq^*$. Statement (iv) is a direct generalization of Pires's result to preferences that are not 1-MEU. Notice that (10) is equivalent to requiring that $f \succcurlyeq_A^* x$ if and only if $fAx \succcurlyeq^* x$, a weakening of (8) that under the assumptions of the proposition is equivalent to it.

It is straightforward to show that dynamic consistency of the primitives $\{\succcurlyeq_A\}_{A\in\Pi'}$ implies condition (ii). Thus, dynamic consistency of the primitives is a sufficient condition for generalized Bayesian updating. The following example reprises the Ellsberg discussion in Sect. 1 to show that it is not necessary.

Example 2. Consider the (CEU and) 1-MEU preference described by (linear utility and) the set $\mathcal{C} = \{P : P(R) = 1/3,\ P(G) \in [1/6, 1/2]\}$. It is clear that a decision maker with such $\mathcal{C}$ would display the preference pattern of (1). It follows from Theorem 1 that her preferences will satisfy consequentialism and unambiguous dynamic consistency if and only if conditionally on $A = \{R, G\}$ her updated set of priors is

$$\mathcal{C}_A = \{P : P(R) \in [2/5, 2/3]\}.$$

Assuming that the decision maker is also 1-MEU conditionally on A, this implies that in period 1 she will still prefer betting on a red ball over betting on a green ball. As discussed in Sect. 1, this cannot happen if the decision maker's conditional preferences satisfy dynamic consistency *tout court*; i.e., (6).

A different way of reinforcing the conditions of Theorem 1 is to consider imposing the full strength of dynamic consistency on the lower envelope preference relations, rather than the weaker form seen in (10). We next show that this leads to the characterization of the notion of rectangularity introduced by Epstein and Schneider (2003).

Suppose that the class Π forms a finite partition of S; i.e., $\Pi = \{A_1, \dots, A_n\}$, with $A_i \cap A_j = \emptyset$ for every $i \neq j$ and $S = \cup_{i=1}^n A_i$. Given a set of probabilities $\mathcal{C}$ such that each A_i is unambiguously nonnull, we define

$$[\mathcal{C}] = \left\{ P : \exists Q, P_1, \dots, P_n \in \mathcal{C} \text{ such that } \forall B \in \Sigma,\ P(B) = \sum_{i=1}^n P_i(B|A_i)\, Q(A_i) \right\}.$$

We say that $\mathcal{C}$ is **Π-rectangular** if $\mathcal{C} = [\mathcal{C}]$.[5] (We refer the reader to Epstein and Schneider (2003) for more discussion of this concept.)

Proposition 5. *Suppose that Π is a partition of S and that every $A \in \Pi$ is unambiguously non-null. Then the following statements are equivalent:*

(i) *$\mathcal{C}$ is Π-rectangular, and for every $A \in \Pi$, $u_A = u$ and $\mathcal{C}_A = \mathcal{C}|A$.*
(ii) *For every $f, g \in \mathfrak{F}$ and $A \in \Pi$:*

$$f \succsim_A^{\downarrow} g \Longleftrightarrow f A g \succsim^{\downarrow} g.$$

The rationale for this result is straightforward: Since the preference $\succsim^{\downarrow}$ is 1-MEU with set of priors $\mathcal{C}$, it follows from the analysis of Epstein and Schneider (2003) that $\mathcal{C}$ is rectangular and that for every $A \in \Pi$, $\mathcal{C}_A$ is obtained by generalized Bayesian updating. But the sets $\mathcal{C}_A$ are also those that represent the ambiguity perception of the primitive relations $\succsim_A$, as they represent the ambiguity perception of $\succsim_A^{\downarrow}$.

We have therefore shown that the characterization of rectangularity and generalized Bayesian updating of Epstein and Schneider can be extended to preferences which do not satisfy ambiguity hedging, having taken care to require dynamic consistency of the lower envelope (or equivalently of the upper envelope), rather than of the primitive, preference relations. The relations between dynamic consistency of the primitives $\{\succsim_A\}_{A\in\Pi'}$ and of the lower envelopes $\{\succsim_A^{\downarrow}\}_{A\in\Pi'}$ are not obvious and are an open research question.

Appendix

We begin with a preliminary remark and two pieces of notation, that are used throughout this appendix. First, notice that since $u(X)$ is convex, it is w.l.o.g. to assume that $u(X) \supseteq [-1,1]$. Second, denote by $B_0(\Sigma, u(X))$ the set of the functions in $B_0(\Sigma)$ that map into $u(X)$. Finally, given a nonempty, convex and weak* compact set $\mathcal{C}$ of probability charges on (S,Σ), we denote for every $\varphi \in B_0(\Sigma)$,

$$\underline{\mathcal{C}}(\varphi) = \min_{P\in\mathcal{C}} P(\varphi), \qquad \overline{\mathcal{C}}(\varphi) = \max_{P\in\mathcal{C}} P(\varphi).$$

Proof of Proposition 2

Since the map from $B_0(\Sigma)$ to $\mathbb{R}$ defined by

$$\psi \mapsto I(u(f)+\psi) - I(\psi)$$

is continuous and $B_0(\Sigma)$ is connected, the set

$$\begin{aligned} J &= \{I(u(f)+\psi) - I(\psi) : \psi \in B_0(\Sigma)\} \\ &= \left\{ I\left(u(f) + \frac{1-\lambda}{\lambda} u(g)\right) - I\left(\frac{1-\lambda}{\lambda} u(g)\right) : g \in \mathfrak{F},\ \lambda \in (0,1] \right\} \end{aligned}$$