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Special Issue on Ambiguity and Strategic Interactions in Honor of Jürgen Eichberger

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To honor the amazing career of Jürgen Eicheberger, this special issue collects ten articles in the field to which he has been actively contributing throughout his career: decision-making under uncertainty. We briefly summarize his academic career, his merits and his achievement in making the new and unorthodox approaches intuitive and broadly applicable in economics. While doing so, we relate the articles of this volume to his contributions.

Jürgen Eichberger graduated in economics from the University in Mannheim in 1977. He started his academic career working on general equilibrium models under the supervision of Volker Böhm. He defended his dissertation on temporary equilibria with financial institutions, Eichberger (1984), and has continued working on the topic of uncertainty and regulation in financial markets throughout his career (see Eichberger, 1989, Eichberger and Summer, 2005, Eichberger et al. 2014).

In 1984, after an assistant professorship at the University of Western Ontario, Jürgen Eichberger accepted a lecturer position at the Australian National University. A request to teach a seminar on game theory sparked his interest in the field. There, he also started the fruitful collaboration with David Kelsey and Simon Grant on decision-making under uncertainly with non-additive beliefs and their applications to games and financial markets. Afterwards, Jürgen Eichberger held positions at the University of Melbourne, Australia, the University of Saarland and the University of Heidelberg in Germany, where he is currently Professor Emeritus. His papers have appeared in major economic journals and contributed to the broad acceptance of the new approaches to decision making under uncertainty among economists. He has also published several books on game theory, financial economics and microeconomics. He is coordinating editor of Theory and Decision and editor of the series Neue ökonomische Grundrisse for Mohr Siebeck.

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At the time Jürgen Eichberger "joined" the decision-theoretic community, non-probabilistic beliefs and non-expected utility representations were still in their infancy. The seminal works of Schmeidler (1989) on Choquet expected utility and Gilboa and Schmeidler (1989) on max–min expected utility have laid the fundamentals by deriving the first representation results, which theoretically, allowed to accommodate the new paradigm of decision-making under uncertainty into economic modeling. However, for most economists, these new developments remained a mathematical curiosity rather than a useful modeling device. Non-expected utility theories relied on the Choquet integral for capacities—a rather complex machinery with little (or so it seemed at the time) intuition or practical application. The price to pay to explain the Ellsberg paradox seemed too high.

Jürgen Eichberger thus set on a journey to make the theory intuitive, tractable and suitable for economic applications. Several challenges had to be addressed before non-additive representations could compete with the classical expected-utility formulations of von Neumann and Morgenstern (1947) and Savage (1954). The specification of non-additive beliefs was problematic for two reasons: first, a capacity has to specify a larger number of variables than a probability distribution and has no obvious empirical equivalent. Second, while probabilistic beliefs can be separated from utility and thus, from the decision-maker's attitude towards risk, a capacity captures simultaneously both the perception of ambiguity, as well as the attitude towards it (Schmeidler, 1989). A simple parametric specification of non-probabilistic (ambiguous) beliefs together with a meaningful way to separate ambiguity perception from ambiguity attitude was a prerequisite to the broad acceptance of the theory to the mainstream of economics and beyond. The model of E(llsberg)-capacities proposed by Eichberger and Kelsey (1999a, 1999b) was among the first parametric approaches to model ambiguous beliefs, which explains how a capacity could incorporate partial probabilistic information, separated from the subjective degree of perceived ambiguity. The NEO-additive capacities, axiomatized by Chateauneuf et al. (2007), fully achieved this goal, while allowing for both optimism and pessimism. They provide an elegant and intuitive parameterization of ambiguity, now widely used in economic applications. A major advantage of this model is that it allows the possibility to incorporate empirical data in the decision-making process (see Eichberger and Guerdjikova, 2013).

The first two papers in this volume, by Grant, Rich and Stecher and by Dominiak and Guerdjikova, are guided by these ideas and provide representations of preferences based on objective, but incomplete, information, which allows for only partial specification of probabilities and leaves room for ambiguity. In Grant et al., this leads to incomplete "objective preferences", which are completed by the Hurwicz criterion. Dominiak and Guerdjikova argue that growing awareness of states might give rise to ambiguity. They provide a parametric preference representation, which generalizes both the E-capacity model and the NEO-additive capacity model in this framework.

Updating of ambiguous beliefs presented a second challenge. In many economic applications, agents have to respond to new information, which requires a dynamic version of the theory. However, there are multiple methods of updating ambiguous beliefs, which allow for modeling optimistic and pessimistic attitudes towards

signals. Behaviorally, updating ambiguous beliefs requires weakening of at least one of the main tenets of Bayesian updating: dynamic consistency or consequentialism. In a series of papers, Eichberger and Grant (1997), Eichberger and Kelsey (1999a, 1999b), Eichberger et al. (2005), Jürgen Eichberger explored the properties of different updating rules trying to identify when and in how far dynamic consistency can be preserved and what classes of preferences are invariant under updating. Eichberger et al. (2007) identified the relaxation of dynamic consistency, which characterizes full Bayesian updating for consequential Choquet expected utility preferences. Eichberger et al. (2012) derive a concept of Generalized NEO-additive capacities, which is characterized by full Bayesian updating. Eichberger et al. (2010) show that for the case of NEO-additive capacities, full Bayesian updating preserves the separation of ambiguity (which might vary with the signal) and ambiguity attitude, which remains constant over time. This makes NEO-additive capacities in combination with full Bayesian updating particularly attractive for applications.

The paper by Vinogradov and Makhlouf in this volume presents an experiment designed to study how beliefs are updated when incoming information is itself ambiguous. Ambiguity-averse subjects are more prone to react to vague news, than ambiguity-neutral ones. The latter, however, tend to ignore some relevant statistical information. The authors attribute this effect to overconfidence.

Randomization plays a crucial role in strategic environments. When players maximize expected utility, linearity of payoffs in strategy mixtures implies indifference towards randomization. An ambiguity-averse player, however, might strictly prefer randomization, if it provides a hedge against the ambiguous behavior of the opponents. Jürgen Eichberger challenged this standard argument. In two insightful papers, Eichberger and Kelsey (1996) and Eichberger et al. (2016), he studied the relationship between ambiguity-averse behavior with respect to non-additive beliefs and preferences for randomization. In Eichberger and Kelsey (1996), he shows that the specific way in which uncertainty, and thus randomization, is modeled plays an important role. While ambiguity-averse decision-makers are always prone to randomize in the Anscombe–Aumann setup, they are indifferent towards randomization in the Savage setup. To shed additional light on this intriguing result, in Eichberger et al. (2016), he related preferences for randomization to dynamic consistency and resolution of uncertainty (ex-ante versus ex-post randomization).

The paper by Oechssler and Roomets in this volume implements experimentally the example of Eichberger and Kelsey (1996). They observe that subjects do behave inconsistently with the hedging-hypothesis formulated in the Anscombe–Aumann setup. Moreover, they show that this puzzling behavior can be rationalized by the before mentioned model of E-capacities within the Savage setup.

Early in his career, Jürgen Eichberger started working on incorporating strategic ambiguity into games. However, a reasonable solution concept for games under ambiguity presented other conceptual difficulties such as finding the appropriate notion of support for non-additive beliefs (Dominiak & Eichberger, 2016; Eichberger & Kelsey, 2014). The first concept of equilibrium under ambiguity was an extension of the Nash equilibrium to allow for non-additive specification of

beliefs over the opponents' strategies and fully pessimistic players, Eichberger and Kelsey (2000). Eichberger and Kelsey (2002) then showed that in games with positive externalities, ambiguity will increase (resp., decrease) the equilibrium contributions in games with strategic complements (resp., substitutes). The concept of equilibrium under ambiguity was then extended to games in which players' beliefs are represented by NEO-additive capacities, Eichberger and Kelsey (2014), accommodating both pessimism and optimism. More recently, in Dominiak and Eichberger (2021), he suggests a simple and tractable version of equilibrium under ambiguity with pessimism and optimism that allows for incorporating exogenous context information in the spirit of Schelling (1960). These novel approaches to modeling strategic ambiguity can not only account for some stylized facts from experiments on coordination (Dominiak & Eichberger, 2021) but can also resolve the multiplicity of equilibria in games (Eichberger et al. 2009). Furthermore, the concept of equilibrium under ambiguity sheds new light on the nature of some of the long-standing paradoxes in game theory by explaining the deviations from Nash equilibrium observed in experiments (Eichberger & Kelsey, 2011).

The paper by Schipper in this volume examines the question of evolutionary stability of optimism and pessimism in aggregative (modular) games. Complete ignorance is evolutionary stable in such games with extreme optimism prevailing in submodular and extreme pessimism in supermodular games.

In sequential games with incomplete information, the issues of updating and dynamic consistency discussed above become highly relevant. Eichberger and Kelsey (2004) provided a solution concept for signaling games under ambiguity. While limited to two-player games and pessimistic updating, the concept of Dempster-Shafer equilibrium was a major conceptual break-through. Besides expanding the field of applications of ambiguity to economic phenomena such as job search, advertising, limit pricing and social norms, it was one of the first equilibrium concepts that allowed for belief updating for information sets off the equilibrium paths. Building on the results on full Bayesian updating reviewed above, Eichberger et al. (2019) formulated a more general equilibrium under ambiguity for sequential games in which players hold NEO-additive beliefs. This concept generalizes the standard concept of backward induction and sequential equilibrium to situations of strategic ambiguity, and can account for observed behavioral anomalies.

In this volume, the paper by Hedlund, Kauffeldt and Lammert provides an example of how optimism and pessimism can impact a persuasion game between an ambiguity-sensitive receiver and an ambiguity-neutral sender. Comparative statics depends on the payoff of the sender's preferred action. If the receiver's payoffs from this action do not vary much with the state, a more pessimistic receiver is easier to persuade to adopt the action and this effect is amplified as ambiguity increases.

Jürgen Eichberger has also been interested in interdisciplinary approaches to decision making. In Eichberger and Pirner (2018), he incorporates the Hilbert space method used in quantum theory to decision theory and to explain the Ellsberg paradox. Besides that, Jürgen Eichberger has also worked on decision and game-theoretic experiments, testing whether ambiguity perception depends on the source of ambiguity, Eichberger et al. (2015), measuring the impact of ambiguity in games,

Eichberger et al. (2008), and the effect of ambiguity on the speed of response, Fiedler et al. (2020).

In this volume, Peryman and Kelsey present an experiment in which they test whether cultural differences might be a source of ambiguity. They find that such an effect is present and leads subjects to choose lower efforts in a coordination game and formulate higher demands in a bargaining game, consistent with the subjects being ambiguity-averse.

While following his research program in decision theory, Jürgen Eichberger has always remained interested in economic applications, both as inspiration for purely theoretical work, as well as a testing ground for the soundness of a theory. He has worked on models of public good provision, Eichberger and Kelsey (2002), auctions, Eichberger and Vinogradov (2015, 2016), speculative trade, Dominiak et al. (2012), financial markets, Eichberger and Guerdjikova (2018), adaptation to climate change, Eichberger and Guerdjikova (2012).

In this volume, the papers by Werner and by Lécuyer and Lefort present applications of ambiguity to financial markets. Werner studies the issue of participation of agents with max–min expected utility preferences in risk-sharing opportunities. He shows that for low levels of aggregate risk, the agents with the most ambiguous beliefs will not bear any risk. This effect is further reinforced if less ambiguous agents are simultaneously less risk-averse. Lécuyer and Lefort apply Generalized NEO-additive capacities to formulate pricing rules for markets with frictions. They identify the type of frictions for which such pricing rules are appropriate and show that the bid-ask spreads are proportional to the range of the potential payoffs of the asset.

Finally, the paper by Ryan applies ambiguity to voting games. When unanimity is required to reach a decision and when penalties to making the wrong decision are asymmetric, under ambiguity, the Jury paradox persists and the probability of reaching a correct decision is bounded away from 1 even if the size of the jury becomes very large.

Jürgen Eichberger's work through the years has influenced many of his colleagues and students, both within and beyond the decision-theoretic community. This volume testifies to the broadness of his ideas and to the influence they have had on the profession. Apart from his qualities as a researcher, those who know Jürgen Eichberger have come to value his personality: his curiosity and his insatiable drive for knowledge and understanding, his willingness to engage in discussion, his work ethic and generosity, his love for books and reading, the warmth and welcome he bestows upon any visitor to the institute or to his home. The authors of this foreword count themselves lucky to be among his students, colleagues and friends and wish to express their deepest gratitude for the guidance, inspiration and encouragement received through the years from their Doktorvater.

References

Chateauneuf, A., Eichberger, J., & Grant, S. (2007). Choice under uncertainty with the best and worst in Mind: NEO-additive capacities. *J Econ Theory, 137,* 538–567.

Dominiak, A., & Eichberger, J. (2016). Support notions for belief functions. *Economics Letters, 146,* 28–32.
Dominiak, A., Eichberger, J. (2021). Games in context: Equilibrium under ambiguity for belief functions. Games and Economic Behavior, Mimeograph, Department of Economics, University of Heidelberg.
Dominiak, A., Eichberger, J., & Lefort, J.-P. (2012). Agreeable trade with optimism and pessimism. *Math Soc Sci, 64,* 119–126.
Eichberger, J. (1984). Geld und kredit in einer ökonomie mit festen preisen. *Ein mikroökonomischer beitrag zur keynesianischen unterbeschäftigungstheorie*. Lang-Verlag.
Eichberger, J. (1989). A note on bankruptcy rules and credit constraints in temporary equilibrium. *Econometrica, 57,* 707–715.
Eichberger, J., & Grant, S. (1997). Dynamically consistent preferences with quadratic beliefs. *J Risk Uncertain, 12,* 189–207.
Eichberger, J., Guerdjikova, A. (2012) Technology adoption and adaptation to climate change - A case-based approach. *Climate Change Economics*. https://doi.org/10.1142/S2010007812500078.
Eichberger, J., & Guerdjikova, A. (2013). Ambiguity, data and preferences for information—a case-based approach. *J Econ Theory, 148,* 1433–1462.
Eichberger, J., & Guerdjikova, A. (2018). Do markets prove pessimists right? *International Economic Review, 59,* 2259–2295.
Eichberger, J., & Kelsey, D. (1996). Uncertainty aversion and preference for randomisation. *J Econ Theory, 71,* 31–43.
Eichberger, J., & Kelsey, D. (1999a). Uncertainty aversion and dynamic consistency. *International Economic Review, 37,* 625–640.
Eichberger, J., & Kelsey, D. (1999b). E-capacities and the Ellsberg paradox. *Theory Decis, 46,* 107–138.
Eichberger, J., & Kelsey, D. (2000). Non-additive beliefs and strategic equilibria. *Games Econ Behav, 30,* 183–215.
Eichberger, J., & Kelsey, D. (2002). Strategic complements, substitutes, and ambiguity: the implications for public goods. *J Econ Theory, 106,* 436–466.
Eichberger, J., & Kelsey, D. (2004). Sequential two-player games with ambiguity. *International Economic Review, 45,* 1229–1261.
Eichberger, J., & Kelsey, D. (2011). Are the treasures of game theory ambiguous? *Economic Theory, 48,* 313–339.
Eichberger, J., & Kelsey, D. (2014). Optimism and pessimism in games. *International Economic Review, 55,* 483–505.
Eichberger, J., & Pirmer, H.-J. (2018). Decision theory with a state of mind represented by an element of a hilbert space: the Ellsberg paradox. *J Math Econ, 78,* 131–141.
Eichberger, J., & Summer, M. (2005). Bank capital, liquidity, and systemic risk. *J Eur Econ Assoc, 3,* 547–555.
Eichberger, J., & Vinogradov, D. (2015). Lowest-unmatched price auctions. *International Journal of Industrial Organization, 43,* 1–17.
Eichberger, J., & Vinogradov, D. (2016). Efficiency of lowest-unmatched price auctions. *Economics Letters, 141,* 98–102.
Eichberger, J., Grant, S., & Kelsey, D. (2005). CEU preferences and dynamic consistency. *Math Soc Sci, 49,* 143–151.
Eichberger, J., Grant, S., & Kelsey, D. (2007). Updating Choquet beliefs. *J Math Econ, 43,* 888–899.
Eichberger, J., Kelsey, D., & Schipper, B. (2008). Granny versus game theorist: ambiguity in experimental games. *Theory Decis, 64,* 333–362.
Eichberger, J., Kelsey, D., & Schipper, B. (2009). Ambiguity and social interaction. *Oxford Econ Papers, 61,* 355–379.
Eichberger, J., Grant, S., & Kelsey, D. (2010). Comparing three ways to update Choquet beliefs. *Economics Letters, 107,* 91–94.
Eichberger, J., Grant, S., & Lefort, J.-P. (2012). Generalized neo-additive capacities and updating. *Int J Econ Theory, 8,* 237–257.
Eichberger, J., Rheinberger, K., & Summer, M. (2014). Credit risk in general equilibrium. *Economic Theory, 57,* 407–435.
Eichberger, J., Oechssler, J., & Schnedler, W. (2015). How do subjects view multiple sources of ambiguity? *Theory and Decision, 78,* 339–356.
Eichberger, J., Grant, S., & Kelsey, D. (2016). Randomization and dynamic consistency. *Economic Theory, 62,* 547–566.

Eichberger, J., Grant, S., & Kelsey, D. (2019). *Strategic ambiguity in multi-stage games with almost perfect information*. Department of Economics, University of Heidelberg.

Fiedler, K., Eichberger, J. Prager, J., McCaughey, L., Schnell, K. (2020) Speed-accuracy tradeoffs in sample-based choices. *Journal of Experimental Psychology: General*, forthcoming. https://doi.org/10.1037/xge0000986.

Gilboa, I., & Schmeidler, D. (1989). Maxmin expected utility with non-unique prior. *J Math Econ, 18,* 141–153.

Savage, L. J. (1954). *The foundations of statistics*. John Willey and Sons.

Schelling, Th. (1960). *The strategy of conflict*. Harvard University Press.

Schmeidler, D. (1989). Subjective probability and expected utility without additivity. *Econometrica, 57,* 571–587.

von Neumann, J., & Morgenstern, O. (1947). *Theory of games and economic behavior*. Princeton University Press.