Review of Economics and Statistics Just Accepted MS.
https://doi.org/10.1162/rest_a_01358

UNRAVELING AMBIGUITY AVERSION*

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Abstract

We report the results of two experiments designed to better understand the mechanisms driving decision-making under ambiguity. We elicit individual preferences over different sources of uncertainty, entailing different degrees of complexity, from subjects with different sophistication levels. We show that (1) ambiguity aversion is robust to sophistication, but the strong relationship previously reported between attitudes toward ambiguity and compound risk is not. (2) Ellsberg ambiguity attitude can be partly explained by attitudes toward complexity for less

*We thank Mohammed Abdellaoui, Aurélien Baillon, Laure Cabantous, Thomas Epper, Helena Hauser, Chen Li, Massimo Marinacci, Sujoy Mukerji, Vincent Théroude, Uyanga Turmunkh, and Peter Wakker for helpful comments and suggestions. We also thank seminar and conference participants at D-TEA, FUR, MUSEES, Bocconi University, Ghent University, and LMU for insightful comments and discussions. We are grateful to Hans-Joachim Zwiesler for the opportunity to run the experiment at ICA 2018 and thank the organizing committee for their help with the experiment. We also thank Diana Valerio for her help with the laboratory experiment. This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement (No 101056891 CAPABLE), the Agence Nationale de la Recherche (ANR-17-CE03-0008-01 INDUCED and ANR-21-CE03-0018 ENDURA), the Region Hauts-de-France (2021.00865 CLAM), and the I-SITE UNLE (project IBEBACC). Logistic support from the Bocconi Experimental Laboratory for the Social Sciences (BELSS) and from the Anthropo-Lab (ETHICS EA 7446) is kindly acknowledged.

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Review of Economics and Statistics Just Accepted MS.
https://doi.org/10.1162/rest_a_01358

sophisticated subjects only. Overall, regardless of the subject's sophistication level, the main driver of Ellsberg ambiguity attitude is a specific treatment of unknown probabilities.

Keywords: Ambiguity aversion, reduction of compound risk, model uncertainty, complexity

JEL Classification: C91-C93-D81

Review of Economics and Statistics Just Accepted MS.
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1 Introduction

For several decades, the standard way to make rational decisions under uncertainty has been to follow Savage's (1954) subjective expected utility (SEU) theory. In 1961, Ellsberg proposed several experiments challenging canonical axioms of SEU. These experiments have given rise to a vast literature studying the phenomenon of ambiguity aversion (i.e., the preference for known probabilities, or *risk*, over unknown probabilities, or *ambiguity*) at both theoretical and empirical levels. However, whether this deviation from SEU constitutes an irrational response to uncertainty or not remains an open question (Gilboa et al., 2009, 2010, 2012; Gilboa and Marinacci, 2013). As ambiguity is present and plays an important role in most real-life decision problems,[1] such a question is critical for normative interpretations of ambiguity attitudes and for the use of ambiguity models in applications with prescriptive purposes. Hence, it has profound implications for policymaking (Berger et al., 2021). Our goal, in this paper, is to clarify the extent to which ambiguity aversion is tied to an arguable mistake, such as the failure to reduce compound lotteries, and study its relationship with the decision-makers' potential limitations or the complexity of a situation.

We explore experimentally decision-making under uncertainty along three dimensions. (1) The first dimension concerns the sources of uncertainty.[2] We investigate attitudes

[1]For example, in financial economics, Mukerji and Tallon (2001) show how ambiguity aversion may lead to incompleteness of financial markets, while Easley and O'Hara (2009) show how it can explain low participation in the stock market despite the potentially high benefits. In the health domain, Berger et al. (2013) show that ambiguity aversion affects treatment decisions. In climate change economics, Drouet et al. (2015) and Berger et al. (2017) show how ambiguity aversion affects optimal emission policies.

[2]Sources of uncertainty are defined as "groups of events that are generated by the same mechanism of uncertainty, which implies that they have similar characteristics" (Abdellaoui et al., 2011, p. 696).

Review of Economics and Statistics Just Accepted MS.
https://doi.org/10.1162/rest_a_01358

toward different sources of risk (presented in simple or compound forms) and ambiguity (presented in the form of *model ambiguity* à la Marinacci (2015)[3] or *ambiguity* à la Ellsberg (1961)). Under SEU, the distinction between these sources is irrelevant: all ambiguous sources are treated as risks through the assignment of subjective probabilities, whereas compound risks are reduced to simple risks in accordance with the reduction of compound lotteries axiom. (2) The second dimension concerns the subjects' level of sophistication. We investigate the preferences of a unique pool of risk professionals (working in insurance related jobs and possessing a high level of education in the fields of mathematics, statistics, or actuarial science) and compare them to those of a convenience sample of university students. Given their background and their training in dealing with computationally complex problems requiring proficiency in probabilistic reasoning, risk professionals can be considered as being more quantitatively "sophisticated" than students. (3) Finally, the third dimension relates to the complexity of the problem. By proposing tasks with varying degrees of complexity within the same source, we are able to isolate the role of complexity in decision-making under risk and ambiguity.

We elicit individual preferences using a two-color Ellsberg-type setting. The large body of existing empirical literature using such a setting has so far highlighted two stylized facts:

SF1: *Individuals are ambiguity averse.*

SF2: *There exists a strong relationship between attitudes towards ambiguity and compound risk.*

SF1 results from the many experiments that have formally tested Ellsberg's (1961) idea, typically using student subjects (L'Haridon et al., 2018; see also the reviews of Machina

[3]Model ambiguity arises when the decision-maker is not able to identify a single probability distribution (among a set of probability models) corresponding to the phenomenon of interest (Hansen, 2014; Marinacci, 2015).

Review of Economics and Statistics Just Accepted MS.
https://doi.org/10.1162/rest_a_01358

and Siniscalchi, 2014; Trautmann and van de Kuilen, 2015).[4] It also typically generalizes to alternative subject pools, including risk professionals (Cabantous, 2007; Cabantous et al., 2011; Hogarth and Kunreuther, 1989). While ambiguity and compound risks have distinct properties, SF2 has been put forward by Halevy (2007), who documented strong similarities in attitudes towards Ellsberg ambiguity and compound risks among student subjects. Based on his findings, Halevy wrote "*The results suggest that failure to reduce compound (objective) lotteries is the underlying factor of the Ellsberg paradox.*" (Halevy, 2007, p. 532). Such findings have been replicated on other student samples (e.g., Chew et al., 2017; Dean and Ortoleva, 2019; Gillen et al., 2019), and on a representative sample of the U.S. population (Chapman et al., 2018). Whether explicitly or implicitly, SF2 has been invoked to challenge the normative status of ambiguity aversion. Specifically, if non-reduction of compound (or, more generally, of complex) risks is considered as a mistake (possibly related to computational difficulties), and if the subjects making this "mistake" are mainly those who are ambiguity non-neutral, there would be little room for using ambiguity models for normative purposes.

Although results in line with SF1 and SF2 have consistently emerged from the literature, their relationship with the subjects' level of sophistication has received little attention so far. Exceptions are the studies of Chew et al. (2018), who investigate the role of subjects' level of comprehension for SF1; and Abdellaoui et al. (2015), and Berger and Bosetti (2020), who report somewhat weaker relationships between ambiguity and compound risk attitudes among engineering students and climate policymakers respectively. Moreover, the role of complexity as a factor contributing to explain SF1 and SF2 remains largely understudied, with the exceptions of Armantier and Treich (2016), and Kovářík et al. (2016). Our paper attempts to fill these gaps by examining two research

[4]We note that ambiguity seeking is also common for ambiguous events with low likelihoods. This local ambiguity seeking attitude is shown to be due to an ambiguity-generated likelihood insensitivity (Dimmock et al., 2015). Our study focuses on probabilities around 50% and does not consider this other component of ambiguity attitudes.

Review of Economics and Statistics Just Accepted MS.
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questions:

RQ1: Are SF1 & SF2 robust to sophistication?

RQ2: What are the main drivers of ambiguity attitude?

To answer these questions, we specifically targeted a sample of risk professionals, who possess a high level of sophistication in probabilistic reasoning. To our knowledge, we are the first to study the preferences of such a unique pool of subjects in an incentivized experiment with a simple, context-free, design allowing us to make direct comparisons with other subject pools. Although focusing on such a unique sample necessarily sacrifices representativeness, it enables us to answer our first research question and to bring novel insights on the role of sophistication. Our second research question aims at disentangling the driving mechanisms of the Ellsberg paradox. Different explanations have been proposed in the literature: Following theories that equate ambiguity to compound risk (e.g., Segal, 1987; Seo, 2009), the driving factor of the Ellsberg paradox is the failure to reduce compound risks.[5] Along similar lines, some recent studies have suggested that ambiguity aversion can be related to an aversion towards complex risks (e.g., Armantier and Treich, 2016; Kovářík et al., 2016). Alternatively, according to a variety of theoretical models with normative underpinnings (see Gilboa and Marinacci, 2013, for a review), Ellsberg-type behaviors are primarily driven by a specific attitude towards unknown probabilities. In what follows, we analyze the effect of these factors to understand their respective roles in explaining SF1 and SF2, and relate them to the subjects' sophistication level.

2 Experiments

We report the results of two experiments. The data were collected in the context of a broad research project investigating the layers of uncertainty (see Aydogan et al.,

[5]Segal (1987, p. 179) wrote: "In other words, risk aversion and ambiguity aversion are two sides of the same coin, and the rejection of the Ellsberg urn does not require a new concept of ambiguity aversion, or a new concept of risk aversion."

Review of Economics and Statistics Just Accepted MS.
https://doi.org/10.1162/rest_a_01358

2023). Specifically, Aydogan et al. (2023) proposed and experimentally tested the *layer hypothesis* by comparing attitudes towards the layers of risk, model ambiguity, and model misspecification. They reported behavioral differences across the three layers based on a main experiment conducted with university students, which was supplemented by robustness experiments conducted with different subject pools (including risk professionals). In the current study, we use a subset of the same data to address the distinct research questions RQ1 and RQ2.[6] In particular, the current study focuses on the contrast between two specific subject pools with distinct characteristics and documents new results on the relationship between uncertainty, sophistication, and the level of complexity.

2.1 Samples

We consider two distinct samples. The main experiment in this study is an artefactual field experiment run on a unique pool of risk professionals (actuaries). The control experiment is a standard laboratory experiment with university students.

Actuaries at ICA We collected data from 84 risk professionals during the 31st International Congress of Actuaries (ICA).[7] The average age was around 40 and 44% of the subjects were female. The subjects were highly educated: 58 subjects (69%) reported a master's degree as the highest level of education completed and 18 subjects (21%) reported a PhD degree. 46 subjects reported that their highest degree was obtained in a field related to mathematics and statistics, while 17 subjects reported it related to actu-

[6] More specifically in the current study, we leave out the treatments involving model misspecification and report on the standard Ellsberg treatment, which is different from the *Extended Ellsberg* treatment reported in the main analysis of Aydogan et al. (2023).

[7] ICA is a conference organized by the International Actuarial Association every four years. It gathers more than 2,500 actuaries, academics, and high-ranking representatives from the international insurance and financial industry. The 31st congress was held from June 4 to 8, 2018, in Berlin, Germany.

Review of Economics and Statistics Just Accepted MS.
https://doi.org/10.1162/rest_a_01358

arial sciences. The remaining subjects reported diplomas in physics (2), engineering (1), finance (1), economics and management (3), or did not report anything (14). Finally, the subjects had an average of 13 years of relevant work experience.

University students We collected data from 125 social science students at Bocconi University, Italy. At the time of the experiment, 80 of them (64%) were in a bachelor's program while 34 (27%) were in a master's program, and the rest (9%) were in a PhD program. 42% of the subjects were female, and the average age was 20.5.

In what follows, we characterize sophistication by the background of the subjects. In that sense, actuaries are considered as more "sophisticated" than students. Such a distinction is justified on the ground that actuaries are experts in decision-making under uncertainty and experienced risk evaluators, who are used to make decisions in situations of ambiguity in their professional roles. They also possess a high training in statistics, probability and decision theory. It should, however, be clear that different dimensions may arguably contribute to making the pool of actuaries different than that of students. In particular, the two samples differ in the following dimensions: (1) *Curriculum*: 79% of the actuaries possess a training in STEM (science, technology, engineering, and mathematics), while the students are in social science programs; (2) *Level of education*: 90% of the actuaries reported to hold at least a master's degree, while this is the case for only 9% of the students; (3) *Experience*: actuaries reported an average 13 years of relevant work experience, whereas most students had no work experience at all. In addition, the age difference between the two groups could be seen as a confounder to what precedes. We report the results of a within-sample heterogeneity analysis in the Online Appendix.

2.2 Design

Sources of uncertainty We use a within subject design to study individual choices under risk and ambiguity. The experiment entails betting on the color of a card drawn from a deck in different situations. We consider the following four distinct sources of uncertainty that are constructed in a two-color Ellsberg-type setting (see also Figure 1

Review of Economics and Statistics Just Accepted MS.
https://doi.org/10.1162/rest_a_01358

(a)).

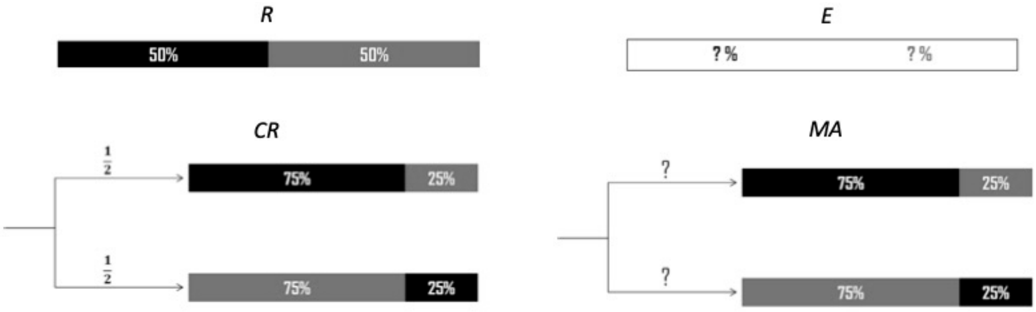
1. (R) *Risk* entails a deck that contains equal proportions of black and red cards.

2. (CR) *Compound Risk* entails, with equal probabilities, either a deck that contains p% red and $(1-p)$% black cards, or a deck that contains p% black and $(1-p)$% red cards.

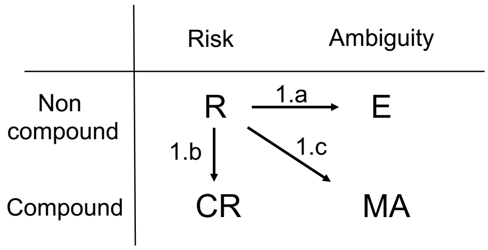
3. (MA) *Model Ambiguity* entails, with unknown probabilities, either a deck that contains p% red and $(1-p)$% black cards, or a deck that contains p% black and $(1-p)$% red cards.

4. (E) *Ellsberg* ambiguity entails a deck of 100 cards that contains an unknown proportion of black and red cards.

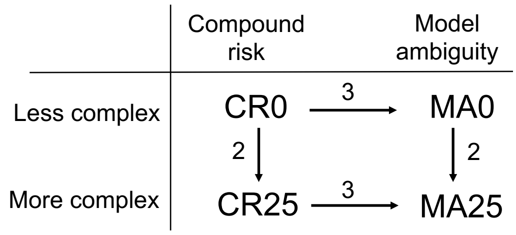
Review of Economics and Statistics Just Accepted MS.
https://doi.org/10.1162/rest_a_01358



(a) Illustration of the four sources of uncertainty (here $p = 25$ in CR and MA)



(b)



(c)

Figure 1: Sources of uncertainty and their characteristics

Review of Economics and Statistics Just Accepted MS.
https://doi.org/10.1162/rest_a_01358

The sources R and CR are two sources of risk (known probabilities), whereas the sources MA and E are ambiguous (unknown probabilities). The sources CR and MA are compounded as they explicitly entail two stages, with two potential deck compositions. They differ from each other in the type of uncertainty they entail in the first stage. Specifically, the two possible deck compositions are unambiguously assigned an objective 50% probability under CR, whereas these probabilities are unknown in the case of MA. On the basis of a symmetry argument, a 50% probability could be assigned to the two possible deck compositions under MA, but these probabilities would then necessarily be subjectively determined.[8] E is the standard ambiguous source originally proposed by Ellsberg (1961).

Complexity We consider a notion of complexity related to the *number of stages of uncertainty* a situation features. Accordingly, for each source CR and MA, we propose two distinct cases that are characterized by different levels of complexity. In the first case, we consider $p = 0$ so that the deck features a degenerate distribution: it contains either 100% black or 100% red cards. We denote the corresponding situations $CR0$ and $MA0$.[9] This case is of minimal complexity: although the situation is presented in two stages, it entails only one stage of uncertainty (as all the uncertainty stems from the first stage). The second case considers $p = 25$, so that the deck contains either 25% red (and 75%

[8] In our experiment, symmetry in the prior distribution stems from the indifference between betting on a red or black card. The symmetry condition can also be justified on the grounds of a general symmetry of information argument: given the information available, there is a priori no reason to believe that one composition deserves more weight than another.

[9] In the literature, $CR0$ has also been used to study the hypothesis of *time neutrality* (Segal, 1987, 1990; Dillenberger, 2010; Nielsen, 2020), i.e., the indifference between early and late resolution of risk. It should be clear that the time dimension is not considered in our experiment.

Review of Economics and Statistics Just Accepted MS.
https://doi.org/10.1162/rest_a_01358

black) cards or 25% black (and 75% red) cards. We denote the corresponding situations $CR25$ and $MA25$.[10]

Procedure Our experiments measure individual preferences over the situations $R, CR0$, $CR25$, $MA0, MA25$, and E. For each of them, the subjects faced a bet on the color of a card randomly drawn from a deck. For every bet, the winning color was determined by the subjects themselves. We elicited the certainty equivalents (CEs) of the bets using a choice-list design. We use the midpoint of an indifference interval implied by a switching point as a proxy for the CE of a bet. In view of the stark income gap between risk professionals and students (see Online Appendix), we adjusted the stakes offered to the two groups by a factor of 10. Specifically, bets yielded either €200 or €0 in the experiment with actuaries and either €20 or €0 in the experiment with students. We used a standard prior within-subject random incentive mechanism in the lab (i.e., all students were paid based on one of their choices) but adopted a between-subject random incentive system in the field (i.e., one-in-ten actuaries was paid) due to budgetary and logistical constraints.[11] The details of the experimental procedures are provided in the Online Appendix.

[10]Note that our characterization of complexity can also be seen as referring to the number of *branches* of a lottery. It is consistent with Chew et al. (2017, see footnote 20) in the case of compound risk, and with the notion of complexity under simple risk, which is typically assessed by the number of different outcomes of the lottery (Sonsino et al., 2002; Moffatt et al., 2015).

[11]Previous literature has reported no systematic difference between paying all subjects or paying one-of-N (Beaud and Willinger 2015; Clot et al. 2018; Berlin et al. 2022). Note also that to further encourage risk professionals to reveal their preferences *conditional* on being selected for payment, we carried out the between-subject randomization *prior* to the experiment, thus enhancing the isolation assumption of Kahneman and Tversky (1979) (see Johnson et al., 2021 for more discussion on the *prior* random incentive mechanisms). Under the isolation assumption, the higher stakes offered to actuaries compensate for the

Review of Economics and Statistics Just Accepted MS.
https://doi.org/10.1162/rest_a_01358

3 A relative premium measure

To examine attitudes toward the different sources of uncertainty, we introduce the following premia measure relative to risk (R).

Definition 1. The relative *premium* $\Pi_{R,j}$ is the difference between the CE of the bet on R (CE_R) and the CE of the bet on j (CE_j), expressed in % of the CE of the bet on the most preferred situation:

$$\Pi_{R,j} \equiv \frac{CE_R - CE_j}{\max\{CE_R, CE_j\}} \qquad \forall j \in \{CR0, CR25, MA0, MA25, E\}\,. \tag{1}$$

Intuitively, two cases can be distinguished. If the individual is relatively more averse to the uncertainty present in situation j, the preferred bet is the one on R, and the relative premium represents the percentage of extra money that an individual would be ready to sacrifice to avoid betting on j, relative to the value of the bet on R. Symmetrically, if the preferred situation is j, the relative premium $\Pi_{R,j}$ represents the extra money that would be sacrificed to avoid betting on R, relative to the value of the bet on j. This index possesses some desirable properties. First, $\Pi_{R,j}$ is symmetric around zero across relatively more or less averse preferences. Second, $\Pi_{R,j}$ belongs to the interval $[-1; 1]$, which also makes it easy to interpret in terms of percentages. Lastly, the normalization with respect to the maximum CE allows more robust comparisons among subject pools by controlling for differences in payoffs and subjects' overall level of uncertainty attitudes.[12]

In the literature, $\Pi_{R,E}$ has been commonly referred to as the *Ellsberg-ambiguity premium* (see, e.g., Berger, 2011; Maccheroni et al., 2013), and $\Pi_{R,CR}$ as the *compound risk*

large income gap between risk professionals and students (see Online Appendix).

[12]In the Online Appendix, we discuss some alternative measures that have been proposed in the literature, such as $\Pi_{R,j} \equiv (CE_R - CE_j)/CE_R$ or $\Pi_{R,j} \equiv (CE_R - CE_j)/(CE_R + CE_j)$ (Sutter et al., 2013; Trautmann and van de Kuilen, 2015). Our conclusions do not differ when using these alternative definitions.

Review of Economics and Statistics Just Accepted MS.
https://doi.org/10.1162/rest_a_01358

premium (see, e.g., Abdellaoui et al., 2015). In the same vein, $\Pi_{R,MA}$ represents the *model ambiguity premium.* These premia are represented by the arrows 1.a-c in Figure 1(b). The relative premium can furthermore be used to measure the effects of complexity and of a specific attitude toward unknown probabilities (in the first stage), as illustrated by arrows 2 and 3 in Figure 1(c). Specifically, as the sources CR and MA both present a relatively less and more complex case (i.e., one stage of uncertainty when $p = 0$ vs. two stages of uncertainty when $p = 25$), the effect of complexity, within each source, can be examined by $(\Pi_{R,CR25} - \Pi_{R,CR0})$ and $(\Pi_{R,MA25} - \Pi_{R,MA0})$. These differences indicate whether the compound risk or model ambiguity premia are larger in more complex cases than in less complex ones. Similarly, $(\Pi_{R,MA0} - \Pi_{R,CR0})$ and $(\Pi_{R,MA25} - \Pi_{R,CR25})$ capture the effect of the distinct treatment of known and unknown probabilities in the first stage within situations entailing the same degree of complexity.

4 Results

Our data consist of six choice lists per subject. Observations with multiple-switching, reverse-switching, or no-switching patterns are not included in the analysis as they do not provide clear measurements of the CEs.[13] We do not detect any order effect on treatments (see Online Appendix).

[13]The proportions of subjects affected by such inconsistencies in at least one of the choice lists are 11.9% for actuaries (10 out of 84) and 10.4% for students (13 out of 125) and do not differ across the two samples (two-sample Z-test of proportions, p=0.73). Discarding four actuaries who show inconsistent patterns in *all* lists, suggesting a lack of attention to the experiment, inconsistencies were present in 16 out of 480 lists (3.3%) for actuaries and in 25 out of 750 lists (3.3%) for students. These proportions are notably lower than what is typically observed in the literature (Yu et al., 2021).

Review of Economics and Statistics Just Accepted MS.
https://doi.org/10.1162/rest_a_01358

4.1 General attitudes toward different sources of uncertainty

Table 1 presents the mean relative premia. We observe that both groups of subjects are comparable in terms of ambiguity premia, exhibiting aversion toward the sources MA and E (t-tests, $p<0.001$).[14] This suggests that ambiguity aversion (SF1) is robust to the subjects' level of sophistication. Regarding the source CR, the average relative premium for $CR25$ is positive for students ($p<0.001$), indicating aversion toward compound risk, but we cannot reject the null hypothesis that $\Pi_{R,CR25} = 0$ for actuaries (t-test, $p=0.03$ but $p=0.17$ after Bonferroni correction[15]). The difference between actuaries and students is particularly marked for this premium (t-test, $p<0.001$). In contrast, the average relative premium for the less complex case $CR0$ does not differ from zero for both groups (t-test, $p=0.59$ for actuaries, and $p=0.55$ for students).

[14]Testing multiple hypotheses (e.g., testing H0 : $\Pi_{R,j} = 0$ for all $j \in \{CR0, CR25, MA0, MA25, E\}$) may require Bonferroni corrections. To allow for direct comparisons with previous literature, we report the original p-values, together with Bonferroni corrections when these affect the results.

[15]The minimum detectable difference from zero mean premium for 5% level of significance (with Bonferroni correction) and a power of 90% is 0.043.

Review of Economics and Statistics Just Accepted MS.
https://doi.org/10.1162/rest_a_01358

Table 1: Average premia relative to risk

	Actuaries	Students	Two-sample tests (p-value)
$\Pi_{R,CR0}$	-0.007 (0.0127)	0.010 (0.0171)	0.472
$\Pi_{R,CR25}$	0.023* (0.0108)	**0.136***** (0.0216)	**<0.001**
$\Pi_{R,MA0}$	**0.121***** (0.0324)	**0.130***** (0.0219)	0.814
$\Pi_{R,MA25}$	**0.106***** (0.0227)	**0.181***** (0.0227)	0.027
$\Pi_{R,E}$	**0.190***** (0.0316)	**0.191***** (0.0249)	0.982

Notes: Standard errors in parentheses. The tests are based on two-sided t-tests. *** significant at 0.001, ** significant at 0.01, * significant at 0.05. Significance stars are based on p-values before Bonferroni correction. Values that are significant at 0.05 after Bonferroni correction are bolded.

Review of Economics and Statistics Just Accepted MS.
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4.2 The relationship between ambiguity and compound risk attitudes

Following the existing literature, we investigate the relationship between attitudes towards ambiguity and compound risk within our two subject pools and test the robustness of SF2 to sophistication. Table 2 reports the Pearson correlation coefficients between compound risk premia and ambiguity premia.[16] In line with SF2, we observe a significant correlation between attitudes toward ambiguity and compound risk for students (except between $\Pi_{R,CR0}$ and $\Pi_{R,E}$, p=0.475). However, such a relationship is absent in the case of actuaries.[17]

[16]The same conclusions are obtained with Spearman rank correlations, which measure monotonic –rather than linear– relationships between premia (see Online Appendix).

[17]We also analyzed correlations based on the method of *obviously related instrumental variables* (ORIV) developed by Gillen et al. (2019) to correct for measurement errors. ORIV uses an instrumental variable approach to compute correlations when there are multiple measurements of behavioral variables. We used ORIV in our data by using multiple elicitations of preferences under compound risk and model ambiguity (i.e., with $p = 0$ and $p = 25$). We observe that, although the correlations between compound risk and ambiguity using ORIV are consistently high for students: corr($\Pi_{R,CR}, \Pi_{R,MA}$)=0.988 and corr($\Pi_{R,CR}, \Pi_{R,E}$)=0.916, they remain remarkably low for actuaries: corr($\Pi_{R,CR}, \Pi_{R,MA}$)=0.369 and corr($\Pi_{R,CR}, \Pi_{R,E}$)=0.057.

Review of Economics and Statistics Just Accepted MS.
https://doi.org/10.1162/rest_a_01358

Table 2: Pearson correlations between compound risk and ambiguity premia

Actuaries				Students			
	$\Pi_{R,MA0}$	$\Pi_{R,MA25}$	$\Pi_{R,E}$		$\Pi_{R,MA0}$	$\Pi_{R,MA25}$	$\Pi_{R,E}$
$\Pi_{R,CR0}$	0.169	-0.033	-0.078	$\Pi_{R,CR0}$	**0.315*****	**0.344*****	0.067
$\Pi_{R,CR25}$	0.135	0.107	0.109	$\Pi_{R,CR25}$	**0.407*****	**0.652*****	**0.475*****

Notes: *** significant at 0.001, ** significant at 0.01, * significant at 0.05. Significance stars are based on p-values before Bonferroni correction. Values that are significant at 0.05 after Bonferroni correction are bolded.

Review of Economics and Statistics Just Accepted MS.
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Next, we examine the links between ambiguity neutrality and reduction of compound risk. We adopted a comprehensive definition of ambiguity neutrality according to which a subject is considered as ambiguity neutral if $\Pi_{R,E} = \Pi_{R,MA0} = \Pi_{R,MA25} = 0$.[18] Similarly, a subject is said to be reducing compound risk if $\Pi_{R,CR0} = \Pi_{R,CR25} = 0$.

The proportion of ambiguity non-neutrality among subjects who do not reduce compound risk is 95% (=20/21) for actuaries and 94% (=77/82) for students. These proportions, which are in line with the literature, suggest that non-reduction of CR is sufficient for ambiguity non-neutrality, irrespective of the subjects' sophistication level. Turning to necessity, we find that 80% (=77/96) of ambiguity non-neutral students are also not reducing CR. However, this proportion is 57% (=20/35) for actuaries, which is significantly less than for students (two-sample test of proportions, p=0.008). This result indicates that, although compound risk non-reduction appears to be also necessary for ambiguity non-neutrality when less sophisticated subjects are considered, this is not the case for more sophisticated ones. Overall, this first set of results enables us to answer RQ1.

Result 1 *(a) Ambiguity aversion is robust to the subjects' sophistication level, but (b) the strong relationship between attitudes toward ambiguity and compound risk is not.*

4.3 Complexity and ambiguity

We now focus on compound sources to examine the effects of complexity and ambiguity in different subject pools. For this, we run a regression analysis with random effects at individual level, where the relative premia $\Pi_{R,j}$ for $j \in \{CR0, CR25, MA0, MA25\}$ are regressed on a dummy for complexity (taking value 1 if $j \in \{CR25, MA25\}$), a dummy for the presence of ambiguity (taking value 1 if $j \in \{MA0, MA25\}$), and their interaction. The baseline is the behavior in a compound risk situation with minimal complexity. To test the effect of sophistication, we run a regression by pooling data from the two samples and using a dummy for actuaries.

[18] Our conclusions are robust to the use of alternative definitions of ambiguity neutrality under MA and E separately (see Online Appendix).

Review of Economics and Statistics Just Accepted MS.
https://doi.org/10.1162/rest_a_01358

Table 3 reports the results. We observe positive coefficients for complexity and model ambiguity, indicating that the relative premia are higher when the situation is more complex or does not entail objective probabilities, in comparison to the less complex situation with objective probabilities (i.e., $CR0$). Therefore, both students and actuaries can be said to be averse to complexity and unknown probabilities in the first-stage. However, the effect of complexity is significantly lower among actuaries than among students, although there is no difference between the two groups regarding the effect of unknown probabilities. We also observe a negative interaction between the variables, suggesting that the effect of complexity is less pronounced in the presence of model ambiguity. This interaction is significant for students but not for actuaries.

Review of Economics and Statistics Just Accepted MS.
https://doi.org/10.1162/rest_a_01358

Table 3: Random Effects Regressions of Relative Premia

	Actuaries	Students	Effect of sophistication (pooled data)
Complexity	0.031*	0.123***	-0.092***
	(0.015)	(0.023)	(0.027)
Model ambiguity	0.128***	0.120***	0.008
	(0.033)	(0.023)	(0.040)
Complexity × Model ambiguity	-0.046	-0.075**	0.028
	(0.031)	(0.026)	(0.040)
Constant	-0.006	0.010	-0.016
	(0.013)	(0.017)	(0.021)
Observations	299	471	770

Notes: Cluster-robust standard errors in parentheses. *** significant at 0.001, ** significant at 0.01, * significant at 0.05. Similar results are obtained when controling for age, gender, income, and education (see Online Appendix).

Review of Economics and Statistics Just Accepted MS.
https://doi.org/10.1162/rest_a_01358

4.4 Explaining Ellsberg ambiguity

Based on what precedes, we now investigate the roles of attitudes toward complexity and unknown probabilities, together with the failure of the reduction principle in explaining Ellsberg-ambiguity attitude. We use the following OLS regression:

$$E\text{-}AMB_i = \beta_0 + \beta_1 COMPX_i + \beta_2 UNKNOWN_i + \beta_3 RED_i + \varepsilon_i, \tag{2}$$

where *Ellsberg* ambiguity attitude ($E\text{-}AMB$) for subject i is computed by $\Pi_{R,E}$. Attitudes toward complexity and unknown probabilities ($COMPX$ and $UNKNOWN$, respectively) are both measured with respect to $\Pi_{R,CR0}$ to isolate their pure effects and avoid interactions between them. Specifically, complexity attitude is captured by $(\Pi_{R,CR25} - \Pi_{R,CR0})$, which computes the difference between the compound risk premia under different degrees of complexity.[19] Attitude toward unknown probabilities is measured by $(\Pi_{R,MA0} - \Pi_{R,CR0})$, which captures the difference in relative premia between two compound situations presenting the same degree of complexity, but different type of probabilities in their first stage.[20] Finally, the measure of reduction (RED) is based on $\Pi_{R,CR0}$: As $CR0$ is arguably the most easily reducible compound risk situation, its non-reduction shows a clear failure of the reduction principle (rather than a failure to deal with complexity). The dummy for (non-) reduction takes 1 if $\Pi_{R,CR0} \neq 0$ and 0 otherwise.

Table 4 reports the results of the regressions. We find that attitude toward unknown probabilities has a positive and significant impact for both actuaries and stu-

[19]Note that the alternative, which is to use $(\Pi_{R,MA25} - \Pi_{R,MA0})$, could be confounded by ambiguity attitudes because $MA0$ may also be seen as being *more ambiguous* than $MA25$ due to a larger spread of first stage probabilities (see Jewitt and Mukerji, 2017; Berger, 2022).

[20]The alternative, which is to use $(\Pi_{R,MA25} - \Pi_{R,CR25})$ could be confounded by risk attitudes because of the presence of risk in the second stage (see the discussion in Berger and Bosetti, 2020).

Review of Economics and Statistics Just Accepted MS.
https://doi.org/10.1162/rest_a_01358

dents. The magnitudes of the coefficients indicate that one percentage point increase in $(\Pi_{R,MA0} - \Pi_{R,CR0})$ leads to 0.74 percentage points increase in $\Pi_{R,E}$ for actuaries, and to 0.43 percentage points increase for students. The difference in this coefficient between the two groups is significant ($p = 0.03$), indicating a stronger effect of attitude toward unknown probabilities for actuaries. In contrast, complexity attitude has a positive and significant impact for students only. The difference in the magnitude of the coefficients between the groups suggests that the effect of complexity is also more pronounced for students (p=0.04). Finally, the positive coefficients of the reduction variable suggest that failure of the reduction principle increases the ambiguity premium, although the coefficients are neither significant nor different in the two groups. Overall, this second set of results enables us to answer RQ2.

Result 2: *(a) For both actuaries and students, the main driver of Ellsberg-ambiguity attitude is a specific treatment of unknown probabilities. (b) A specific attitude toward complexity is found to play a significant role in explaining Ellsberg-ambiguity attitude for students only.*

Review of Economics and Statistics Just Accepted MS.
https://doi.org/10.1162/rest_a_01358

Table 4: OLS Regressions of Ellsberg Ambiguity Premium

	Actuaries	Students	Difference between groups (pooled data)
COMPX	-0.170	0.253*	-0.423*
	(0.167)	(0.116)	(0.203)
UNKNOWN	0.735***	0.434***	0.302*
	(0.091)	(0.106)	(0.140)
RED	0.137	0.036	0.101
	(0.074)	(0.048)	(0.088)
Constant	0.079**	0.091***	-0.012
	(0.026)	(0.024)	(0.036)
Observations	74	114	188

Notes: Robust standard errors in parentheses, *** significant at 0.001, ** significant at 0.01, * significant at 0.05. Simlar results are obtained when controling for age, gender, income, and education.

Review of Economics and Statistics Just Accepted MS.
https://doi.org/10.1162/rest_a_01358

5 Concluding remarks

Decisions made by unusual subject pools, such as climate policymakers (Berger and Bosetti, 2020), professional traders (Fox et al., 1996), professional chess players (Levitt et al., 2011), or golf players (Pope and Schweitzer, 2011) have been the focus of studies trying to explain important behavioral phenomena. Following this line of research, we focus on a unique pool of risk professionals to re-examine two stylized facts about ambiguity attitudes, which have emerged in the literature. Because these professionals routinely price risk and uncertainty at work, their occupational practice makes them of special interest for studying decision-making under uncertainty.

Our results show that this selected group of subjects is as much affected by ambiguity as a standard pool of university students. However, attitudes towards ambiguity and compound risk are less closely related for risk professionals than for students. In particular, compound risk non-reduction is found sufficient but not necessary for ambiguity non-neutrality for these more sophisticated subjects. We argue that attitudes toward complexity may explain these findings. Indeed, if ambiguity is viewed as a compound source of uncertainty, or presented as such (as in model ambiguity situations), non-reduction of compound risk can be sufficient for ambiguity non-neutrality. On the other hand, if complexity makes compound risk situations being perceived as ambiguous by some subjects, those who are ambiguity non-neutral will also exhibit compound risk non-reduction (and hence the necessity). Interestingly, this effect is significantly weaker for more sophisticated subjects, who are less affected by the complexity of a situation. Consistent with this interpretation, we observe that a non-negligible proportion of ambiguity non-neutral actuaries *do* actually reduce compound risk.

The paper closest to ours is Abdellaoui et al. (2015), who compared two student samples differing in their training (engineering vs. non-engineering fields). While they also report a somewhat weaker link between compound risk and ambiguity for more quantitatively sophisticated students, the differences they find between their two student samples are not as stark as those between students and actuaries. By studying a pool of

Review of Economics and Statistics Just Accepted MS.
https://doi.org/10.1162/rest_a_01358

risk professionals, whose contrast with students is more extreme, our study may be seen as more revealing for the role of sophistication in decision-making. Yet we also note that differences in sophistication might exist within the populations studied. An additional analysis of our data indeed indicates some heterogeneity among students but not among risk professionals (for the details, see Online Appendix). For example, undergraduate students are found to be more affected by complexity than graduate ones, whereas work experience (or age) is not found to play any role among actuaries.

We argue that our findings may have important implications for different ambiguity models. Overall, by suggesting that ambiguity aversion is mainly driven by a genuine preference for known probabilities over unknown ones, but not necessarily by an inability/aversion to deal with the compoundness or complexity of a situation, the results we report in this paper are more consistent with the predictions of ambiguity theories with normative underpinnings. Thus, they leave room for using ambiguity models in applications with prescriptive purposes.

Review of Economics and Statistics Just Accepted MS.
https://doi.org/10.1162/rest_a_01358

References

Abdellaoui, Mohammed, Aurélien Baillon, Laetitia Placido, and Peter P Wakker (2011) "The rich domain of uncertainty: Source functions and their experimental implementation," *The American Economic Review*, 101 (2), 695–723.

Abdellaoui, Mohammed, Peter Klibanoff, and Lætitia Placido (2015) "Experiments on Compound Risk in Relation to Simple Risk and to Ambiguity," *Management Science*, 61 (6), 1306–1322.

Armantier, Olivier and Nicolas Treich (2016) "The Rich Domain of Risk," *Management Science*, 62, 1954–1969.

Aydogan, Ilke, Loïc Berger, Valentina Bosetti, and Ning Liu (2023) "Three Layers of Uncertainty," *Journal of the European Economic Association*.

Beaud, Mickael and Marc Willinger (2015) "Are people risk vulnerable?" *Management Science*, 61 (3), 624–636.

Berger, Loïc (2011) "Smooth Ambiguity Aversion in the Small and in the Large," Working Papers ECARES 2011-020, ULB – Université libre de Bruxelles.

Berger, Loïc (2022) "What is Partial Ambiguity?" *Economics and Philosophy*, 38 (2), 206–220.

Berger, Loïc, Nicolas Berger, Valentina Bosetti, Itzhak Gilboa, Lars Peter Hansen, Christopher Jarvis, Massimo Marinacci, and Richard D. Smith (2021) "Rational Policymaking during a Pandemic," *Proceedings of the National Academy of Science*, 118 (4), e2012704118.

Review of Economics and Statistics Just Accepted MS.
https://doi.org/10.1162/rest_a_01358

Berger, Loïc, Han Bleichrodt, and Louis Eeckhoudt (2013) "Treatment decisions under ambiguity," *Journal of Health Economics*, 32 (3), 559–569.

Berger, Loïc and Valentina Bosetti (2020) "Are Policymakers Ambiguity Averse?" *The Economic Journal*, 130, 331–355.

Berger, Loïc, Johannes Emmerling, and Massimo Tavoni (2017) "Managing Catastrophic Climate Risks Under Model Uncertainty Aversion," *Management Science*, 63 (3), 749–765.

Berlin, Noemie, Emmanuel Kemel, Vincent Lenglin, and Antoine Nebout-Javal (2022) "A convenient truth : between-subject random incentives and preferences towards risk and time," mimeo.

Cabantous, Laure (2007) "Ambiguity aversion in the field of insurance: Insurers' attitude to imprecise and conflicting probability estimates," *Theory and Decision*, 62 (3), 219–240.

Cabantous, Laure, Denis Hilton, Howard Kunreuther, and Erwann Michel-Kerjan (2011) "Is imprecise knowledge better than conflicting expertise? Evidence from insurers' decisions in the United States," *Journal of Risk and Uncertainty*, 42 (3), 211–232.

Chapman, Jonathan, Mark Dean, Pietro Ortoleva, Erik Snowberg, and Colin Camerer (2018) "Econographics,"Technical report, National Bureau of Economic Research.

Chew, Soo Hong, B. Miao, and S. Zhong (2017) "Partial Ambiguity," *Econometrica*, 85 (4), 1239–1260.

Chew, Soo Hong, Mark Ratchford, and Jacob S. Sagi (2018) "You Need to Recognise Ambiguity to Avoid It," *The Economic Journal*, 128 (614), 2480–2506.

Review of Economics and Statistics Just Accepted MS.
https://doi.org/10.1162/rest_a_01358

Clot, Sophie, Gilles Grolleau, and Lisette Ibanez (2018) "Shall we pay all? An experimental test of Random Incentivized Systems," *Journal of Behavioral and Experimental Economics*, 73, 93–98.

Dean, Mark and Pietro Ortoleva (2019) "The empirical relationship between nonstandard economic behaviors," *Proceedings of the National Academy of Sciences*, 116 (33), 16262–16267.

Dillenberger, David (2010) "Preferences for one-shot resolution of uncertainty and Allais-type behavior," *Econometrica*, 78 (6), 1973–2004.

Dimmock, Stephen G, Roy Kouwenberg, and Peter P Wakker (2015) "Ambiguity Attitudes in a Large Representative Sample," *Management Science*, null.

Drouet, Laurent, Valentina Bosetti, and Massimo Tavoni (2015) "Selection of Climate Policies under the uncertainties in the Fifth Assessment Report of the IPCC," *Nature Climate Change*, 5, 937–940.

Easley, David and Maureen O'Hara (2009) "Ambiguity and nonparticipation: The role of regulation," *The Review of Financial Studies*, 22 (5), 1817–1843.

Ellsberg, Daniel (1961) "Risk, ambiguity, and the Savage axioms," *The Quarterly Journal of Economics*, 75, 643–669.

Fox, Craig R, Brett A Rogers, and Amos Tversky (1996) "Options traders exhibit subadditive decision weights," *Journal of Risk and uncertainty*, 13 (1), 5–17.

Gilboa, Itzhak, Fabio Maccheroni, Massimo Marinacci, and David Schmeidler (2010) "Objective and subjective rationality in a multiple prior model," *Econometrica*, 78 (2), 755–770.

Review of Economics and Statistics Just Accepted MS.
https://doi.org/10.1162/rest_a_01358

Gilboa, Itzhak and Massimo Marinacci (2013) "Ambiguity and the Bayesian paradigm," in *Advances in Economics and Econometrics: Theory and Applications, Tenth World Congress of the Econometric Society.*: D. Acemoglu, M. Arellano, and E. Dekel (Eds.). New York: Cambridge University Press.

Gilboa, Itzhak, Andrew Postlewaite, and David Schmeidler (2009) "Is it always rational to satisfy Savage's axioms?" *Economics and Philosophy*, 25 (3), 285–296.

——— (2012) "Rationality of belief or: why Savage's axioms are neither necessary nor sufficient for rationality," *Synthese*, 187 (1), 11–31.

Gillen, Ben, Erik Snowberg, and Leeat Yariv (2019) "Experimenting with measurement error: Techniques with applications to the caltech cohort study," *Journal of Political Economy*, 127 (4), 1826–1863.

Halevy, Yoram (2007) "Ellsberg revisited: An experimental study," *Econometrica*, 75 (2), 503–536.

Hansen, Lars Peter (2014) "Nobel Lecture: Uncertainty Outside and Inside Economic Models," *Journal of Political Economy*, 122 (5), 945–987.

Hogarth, Robin M and Howard Kunreuther (1989) "Risk, ambiguity, and insurance," *Journal of Risk and Uncertainty*, 2 (1), 5–35.

Jewitt, Ian and Sujoy Mukerji (2017) "Ordering Ambiguous Acts," *Journal of Economic Theory*, 171, 213–267.

Johnson, Cathleen, Aurélien Baillon, Han Bleichrodt, Zhihua Li, Dennie Van Dolder, and Peter P Wakker (2021) "Prince: An improved method for measuring incentivized preferences," *Journal of Risk and Uncertainty*, 1–28.

Review of Economics and Statistics Just Accepted MS.
https://doi.org/10.1162/rest_a_01358

Kahneman, Daniel and Amos Tversky (1979) "Prospect theory: An analysis of decision under risk," *Econometrica*, 47 (2), 363–391.

Kovářík, Jaromír, Dan Levin, and Tao Wang (2016) "Ellsberg paradox: Ambiguity and complexity aversions compared," *Journal of Risk and Uncertainty*, 52 (1), 47–64.

Levitt, Steven D, John A List, and Sally E Sadoff (2011) "Checkmate: Exploring backward induction among chess players," *American Economic Review*, 101 (2), 975–90.

L'Haridon, Olivier, Ferdinand M Vieider, Diego Aycinena, Agustinus Bandur, Alexis Belianin, Lubomir Cingl, Amit Kothiyal, and Peter Martinsson (2018) "Off the charts: Massive unexplained heterogeneity in a global study of ambiguity attitudes," *Review of Economics and Statistics*, 100 (4), 664–677.

Maccheroni, Fabio, Massimo Marinacci, and Doriana Ruffino (2013) "Alpha as Ambiguity: Robust Mean-Variance Portfolio Analysis," *Econometrica*, 81 (3), 1075–1113.

Machina, Mark J and Marciano Siniscalchi (2014) "Ambiguity and ambiguity aversion," in *Handbook of the Economics of Risk and Uncertainty*, 1, 729–807: Elsevier.

Marinacci, Massimo (2015) "Model Uncertainty," *Journal of the European Economic Association*, 13 (6), 1022–1100.

Moffatt, Peter G, Stefania Sitzia, and Daniel John Zizzo (2015) "Heterogeneity in preferences towards complexity," *Journal of Risk and Uncertainty*, 51 (2), 147–170.

Mukerji, Sujoy and Jean-Marc Tallon (2001) "Ambiguity aversion and incompleteness of financial markets," *The Review of Economic Studies*, 68 (4), 883–904.

Nielsen, Kirby (2020) "Preferences for the resolution of uncertainty and the timing of information," *Journal of Economic Theory*, 189, 105090.

Review of Economics and Statistics Just Accepted MS.
https://doi.org/10.1162/rest_a_01358

Pope, Devin G and Maurice E Schweitzer (2011) "Is Tiger Woods loss averse? Persistent bias in the face of experience, competition, and high stakes," *American Economic Review*, 101 (1), 129–57.

Savage, Leonard J (1954) *The Foundations of Statistics*, New York: J. Wiley, Second revised edition, 1972.

Segal, Uzi (1987) "The Ellsberg paradox and risk aversion: An anticipated utility approach," *International Economic Review*, 175–202.

——— (1990) "Two-stage lotteries without the reduction axiom," *Econometrica*, 349–377.

Seo, Kyoungwon (2009) "Ambiguity and Second-Order Belief," *Econometrica*, 77 (5), 1575–1605.

Sonsino, Doron, Uri Benzion, and Galit Mador (2002) "The complexity effects on choice with uncertainty–Experimental evidence," *The Economic Journal*, 112 (482), 936–965.

Sutter, Matthias, Martin G Kocher, Daniela Glätzle-Rützler, and Stefan T Trautmann (2013) "Impatience and uncertainty: Experimental decisions predict adolescents' field behavior," *American Economic Review*, 103 (1), 510–31.

Trautmann, Stefan T. and Gijs van de Kuilen (2015) *Ambiguity Attitudes*, Chap. 3, 89–116: The Wiley Blackwell Handbook of Judgment and Decision Making, John Wiley & Sons, Ltd.

Yu, Chi Wai, Y Jane Zhang, and Sharon Xuejing Zuo (2021) "Multiple switching and data quality in the multiple price list," *Review of Economics and Statistics*, 103 (1), 136–150.