TESTING AXIOMATIZATIONS OF AMBIGUITY AVERSION

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Abstract The study of choice under uncertainty has advanced through key "paradoxes," such as the Ellsberg paradox. We implement Machina's (2014) three-outcome extension, in which four major ambiguity-aversion theories (multiple priors, rank-dependent, smooth ambiguity, variational) all predict indifference between two ambiguous acts. Contrary to these predictions, we find most participants do not express indifference. Our design elicits each subject's certainty equivalent (CE) for an embedded 50–50 lottery and uses that CE in the Machina acts. Under lottery independence—i.e., if individuals apply standard (von Neumann–Morgenstern) expected utility to each objective lottery—these acts map to the same distribution of payoffs and thus should be evaluated identically. Yet we document a robust preference for one act over the other. This preference is associated with violations of lottery independence (e.g., Allais inconsistencies), as well as with disappointment aversion. Our results highlight that Machina's three-outcome paradox is at least as much about failing independence over lotteries as it is about ambiguity aversion.

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Keywords: Ellsberg paradox, Machina paradox, uncertainty aversion, independence axiom

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1. INTRODUCTION

The development of the normative and positive theory of behavior under uncertainty is characterized by a series of thought experiments to which scholars or laypersons often give answers that contradict prevailing theory. The St.-Petersburg-Paradox challenged the notion that a lottery will be evaluated by its expected value (de Montmort 1713). Bernoulli (1738) proposed a concave utility function instead of the payoffs themselves. Allais (1953) subsequently proposed a thought experiment demonstrating that many people do not exhibit the behavior suggested by Bernoulli and von Neumann and Morgenstern's expected utility theory. Ellsberg (1961) further challenged the notion that decision-makers have a single subjective probability distribution (i.e., are probabilistically sophisticated) with a thought experiment involving choice over ambiguity (Feduzi 2007). Empirical papers (for a survey see Camerer and Weber, 1992) showed that people behave differently than probabilistic sophistication prescribes. New models were proposed to accommodate the ambiguity non-neutrality observed in the Ellsberg experiment. The four prevailing theories are: Schmeidler's (1989) Choquet model (or Rank-Dependent Utility); Gilboa and Schmeidler's (1989) maximin expected utility; Klibanoff et al.'s (2005) smooth ambiguity; and Maccheroni et al.'s (2006) Variational Preferences Model. Ambiguity attitudes are now used to explain puzzles in finance (Erbas and Mirakhor 2007), promote policies in health (Sutter et al. 2013), law (Segal and Stein 2005), and the environment (Viscusi and Zeckhauser 2006), and explain phenomena in the lab (Liu and Colman 2009; Ball et al. 2012; Baillon et al. 2016).

A thought experiment challenges the prevailing four theories. Machina (2014) proposes two ambiguous acts, where the four models all predict indifference. The thought experiment involves three outcomes (classic Ellsberg urns never have more than two outcomes) as shown below. An urn contains 3 balls, exactly 1 of which is red, while the other two could be both white, both black, or one white and one black ball. The outcomes in this Machina thought experiment are monetary prizes of \$0, \$$c$ and \$100, where \$$c \sim (\frac{1}{2}, \$0; \frac{1}{2}, \$100)$, the certainty equivalent of the lottery of receiving \$100 with probability 50% and else \$0.

	Act L				Act H	
1-3 5-7	2 balls	1 ball		1 ball	2 balls	
Black	White	Red		Red	Black	White
\$0	\$$c$	\$100		\$0	\$$c$	\$100

A central feature of Machina's three-outcome paradox is that it combines both subjective and objective uncertainty. The subjective uncertainty involves which state of the world obtains—e.g., whether the unknown balls in the urn are black or white—while the conditional objective uncertainty concerns the probability of drawing a particular ball color within that state (e.g., a 2/3 chance of drawing black in state BB). Purely subjective or purely objective uncertainty alone typically does not generate the same kind of paradoxical prediction.

The broader literature has recognized that blending subjective and objective components can create richer paradoxes that challenge classical expected utility. For instance, Machina (2014) himself emphasizes that many major models of ambiguity (such as multiple priors, rank-dependent, smooth ambiguity, or variational preferences) allow for ambiguity in the state probabilities but still impose von Neumann–Morgenstern (vNM) expected utility on the conditional objective lotteries. Under these models, Machina's act L and act H end up having the same overall distribution of payoffs—hence predict indifference.

This underscores a key limitation in existing ambiguity theories: they typically do not relax how people evaluate the conditional (objective) lottery. As a result, any re-arrangement of payoffs among states that preserves the same final distribution yields indifference. However, according to Machina (2014), "If ambiguity aversion somehow involves 'pessimism,' might not an ambiguity averter have a strict preference for [Act] H over [Act] L, just as a risk averter might prefer bearing risk about higher rather than lower outcome levels?" Our key contribution is to implement the Machina "ambiguity at low vs. at high problem with three colors" thought experiment.

We employ a two-part experimental design to elicit each subject's certainty equivalent (CE) of a simple 50–50 lottery and then use that CE as one of the possible outcomes in the Machina (2014) thought experiment. We implement this using the PRINCE (PRior INCEntive) method (Johnson et al. 2021), which is formally equivalent to BDM (Becker et al. 1964a) but allows us to pre-randomize the implemented choice. This design choice enables us to present subjects with all instructions at the beginning, avoid additional strategic considerations between parts, and maintain transparent incentives.

In brief, the subject first states, for every possible monetary amount X, whether they would prefer X in cash or the 50–50 lottery (the "CE task"). Then, for the Machina task, each subject makes choices between two ambiguous acts L and H, for each possible value of X. By drawing a single randomly selected value of X before the experiment (and placing it in a sealed envelope), we ensure that there are clear, pre-determined incentives. This approach directly connects the CE task and the Machina task without introducing separate or hidden randomization later. In our experimental implementation, subjects are not indifferent between Acts L and H. On average, subjects prefer Act L over Act H. We use Dillenberger and Segal (2015) in combination with Gul's (1991) disappointment aversion to give conditions under which Act L or Act H is preferred.

We contribute evidence that distinguishes between theoretical foundations of ambiguity aversion. Machina also proposed earlier thought experiments in Machina (2009). Machina distinguishes his 2014 thought experiment, which is based on a single source of purely subjective uncertainty, unlike Machina (2009), which is based on two. Baillon et al. (2011) and L'Haridon and Placido (2010) theoretically and empirically investigated Machina's 2009 thought experiment. Their results complement ours, and together, advance the argument that the Machina paradoxes falsify many ambiguity theories, at least in the Anscombe-Aumann framework adopted by those theories with the vNM independence axiom as central. The remainder of the paper is organized as follows. Section 2 outlines Machina's three-outcome thought experiment and explains why major ambiguity models predict indifference. Section 3 describes our lab study's design and reports key findings. Finally, Section 4 offers concluding remarks.

2. MACHINA THOUGHT EXPERIMENT

Machina (2014) proposes a paradox involving mixed subjective and objective uncertainty. Consider an urn with three balls, exactly one of which is red, while the other two might be:

- Both black (BB),
- Both white (WW),
- One black and one white (BW).

A decision maker (DM) faces *subjective* uncertainty about which of these states obtains (i.e., the DM may not know the probabilities $q_{\mathrm{BB}}, q_{\mathrm{WW}}, q_{\mathrm{BW}}$), but once a state is realized, the probability of drawing a specific color in that state is *objectively* determined.

Let \$c be the DM's certainty equivalent (CE) of a simple 50–50 lottery paying \$0 or \$100. We study two acts, L (ambiguity at low payoffs) and H (ambiguity at high payoffs).

Table 1 illustrates, for each of the two acts, the *objective probability distribution* over outcomes for each state, as well as the corresponding *vNM expected utility*.

TABLE I

vNM UTILITY FOR ACTS L AND H

State	**Act** L	**Act** H	**vNM Utility L**	**vNM Utility H**
BB	$(\frac{2}{3}, 0;\ \frac{1}{3}, 100)$	$(\frac{1}{3}, 0;\ \frac{2}{3}, c)$	$\frac{2}{3}\,u(0) + \frac{1}{3}u(100)$	$\frac{1}{3}u(0) + \frac{2}{3}\,u(c)$
BW	$(\frac{1}{3}, 0;\ \frac{1}{3}, c;\ \frac{1}{3}, 100)$	$(\frac{1}{3}, 0;\ \frac{1}{3}, c;\ \frac{1}{3}, 100)$	$\frac{1}{3}\,u(0) + \frac{1}{3}\,u(c) + \frac{1}{3}u(100)$	$\frac{1}{3}u(0) + \frac{1}{3}u(c) + \frac{1}{3}u(100)$
WW	$(\frac{2}{3}, c;\ \frac{1}{3}, 100)$	$(\frac{1}{3}, 0;\ \frac{2}{3}, 100)$	$\frac{2}{3}\,u(c) + \frac{1}{3}\,u(100)$	$\frac{1}{3}u(0) + \frac{2}{3}\,u(100)$

The last two columns in Table I show the vNM expected utility for each objective lottery given a utility function u over monetary outcomes. Normalizing $u(0) = 0$ and $u(100) = 100$, it follows that $u(c) = 50$. As a result, we have the following. In BB and BW, both acts yields a vNM utility of 1/3, and in WW, both acts yields a vNM utility of 2/3. Hence, both Acts L and H yield the *same* mapping from states to vNM utilities, and *any aggregator* that just forms a (subjective) weighted sum over those utilities will yield the same overall utility for Acts L and H. For instance, suppose a DM's beliefs about $\mathrm{BB}, \mathrm{BW}, \mathrm{WW}$ lie within some set of priors $p \in \Delta$. Under *multiple-priors utility*, the DM evaluates each act by

$$V(\text{Act}) = \min_{\mathbf{p}\in\Delta} \left[p_{\text{BB}}\, U_{\text{BB}}(\text{Act}) \; + \; p_{\text{BW}}\, U_{\text{BW}}(\text{Act}) \; + \; p_{\text{WW}}\, U_{\text{WW}}(\text{Act})\right].$$

If $U_s(\cdot)$ is the vNM expected utility of the conditional lottery, then each prior $\mathbf{p}$ assigns the *same row-wise utility* for L and H, thus $V(L) = V(H)$.

2.1. *Disappointment aversion*

Suppose instead that, *rather than* vNM expected utility, the DM evaluates objective lotteries in terms of a disappointment-averse (DA) utility (Gul 1991). Disappointment aversion generalizes vNM expected utility: in addition to the utility u over monetary outcomes, a parameter $\beta > 0$ that penalizes outcomes below a lottery's mean. DA collapses to vNM if and only if $\beta = 0$. Table 2 gives the DA utility for each of the states for Acts L and H (with the same normalization for u as in Table 1). (The calculations for Table 2 are in our online appendix.)

TABLE II

DA UTILITY FOR ACTS L AND H

State	**Act** L	**Act** H	**DA Utility** L	**DA Utility** H
BB	$(\frac{2}{3}, 0;\ \frac{1}{3}, 100)$	$(\frac{1}{3}, 0;\ \frac{2}{3}, c)$	$\dfrac{100}{3+2\,\beta}$	$\dfrac{100}{3+\beta}$
BW	$(\frac{1}{3}, 0;\ \frac{1}{3}, c;\ \frac{1}{3}, 100)$	$(\frac{1}{3}, 0;\ \frac{1}{3}, c;\ \frac{1}{3}, 100)$	$\dfrac{150}{3+\beta}$	$\dfrac{150}{3+\beta}$
WW	$(\frac{2}{3}, c;\ \frac{1}{3}, 100)$	$(\frac{1}{3}, 0;\ \frac{2}{3}, 100)$	$\dfrac{(2/3)(1+\beta)\,50\; + \;(1/3)\,100}{1+\beta\,(2/3)}$	$\dfrac{200}{3+\beta}$

When $\beta > 0$, the DA utility of the objective lottery in states BB or WW differs for acts L and H. As a result, an aggregate of the DA utilities in the states can lead to a different value for the two acts. For instance, suppose a decision maker evaluates lotteries in terms of the DA utilities in Tables 2, and entertains multiple priors over the subjective states. Specifically, suppose $P(\text{BW}) = 1/3$ and $P(\text{BB}) \in [0, 2/3]$, with $P(\text{WW}) = 2/3 - P(\text{BB})$. Then, it is easily verified that $V(L) > V(H)$.

2.2. *Limitations of the Anscombe–Aumann Approach*

Like Machina (2014), we adopt the Anscombe–Aumann (AA) framework, which imposes vNM expected utility at the *lottery* level. This separation of subjective vs. objective uncertainty is analytically convenient but not universal. As noted in Wakker (2024, p. 1838), *rank-dependent utility* without the AA assumption could accommodate preferences that break $L \sim H$ by relaxing the requirement of vNM independence for conditional risk. Thus, while we treat $L \sim H$ as a contradiction for multiple priors, rank-dependent/Choquet, smooth, or variational models *under AA*, other non-AA formulations may avoid the paradox.

Indeed, under Savage-based or purely statewise models, such as RDU without AA, a decision maker can be "ambiguity-seeking" for low-likelihood events and "ambiguity-averse" for high-likelihood events, thereby breaking indifference *even* if they hold "Choquet-style" beliefs over states. However, once we impose Anscombe–Aumann's monotonicity or substitutability, the same rank-dependent (or multiple priors, or smooth, etc.) aggregator will yield indifference between Acts L and H if the DM applies standard expected utility *within* each conditional lottery. Thus, the "contradiction" we highlight primarily concerns these four major theories *within* the AA framework (see also Machina 2014).

Consequently, our experimental findings should be interpreted with the caveat that they directly test these models *under the Anscombe–Aumann assumption* of vNM evaluation for risk. We acknowledge that non-AA versions of RDU or other ambiguity models (i.e., those not imposing vNM on conditional lotteries) may well accommodate the strict preferences we observe without contradiction.

3. LAB STUDY

3.1. *Design*

We ran the lab experiment at the DeSciL lab following their standard procedures in ETH Zurich using paper-and-pencil, for reasons described below. We had 91 participants across 6 sessions. Rather than replacing $\$c$ with the lottery it is induced by as in Figure 1, we sought to recover $\$c$ through revealed preference. If the decision-maker has a preference relation which satisfies continuity, then a certainty equivalent is guaranteed to exist; strict monotonicity in the monetary outcomes ensures uniqueness. However, the certainty equivalent of a subject is unknown to the experimenter.

The main challenge is to elicit the subject's certainty equivalent prior to conducting the Machina "ambiguity at low vs. at high problem with three colors" thought experiment. The state-of-the-art method to experimentally elicit willingness to pay for an object is still BDM (Becker et al. 1964b). BDM can be implemented by the mechanism itself or a simplified "list" method. In the mechanism, people are asked to state their true valuation, a price is randomly drawn, and they receive the object at the random price if their stated valuation is above it. In the "list" method, people are presented with a list of choices, each consisting of two options, the object and a valuation, and one of the indicated choices is then selected at random. From a formal point of view, the two are close cousins, the difference being that in the list method the valuation one can state is quite coarse. Regardless of the method, subjects are usually told that correctly stating their true valuation is optimal.

We implement a two-part design. In Part 1 (the "CE task"), each participant states, for every possible value of $X \in \{0, 1, \ldots, 20\}$, whether they prefer receiving X in cash or playing a 50–50 lottery that pays \$100 or \$0. This allows us to infer each individual's certainty equivalent (CE). In Part 2 (the "Machina task"), participants compare Act L and Act H for every possible value of X.

Before the experiment begins, a sealed envelope with a random integer X (between 0 and 20) is prepared for each participant. That random X is relevant in both parts: in Part 1, subjects effectively give instructions for each possible X; in Part 2, they again indicate whether they prefer Act L or Act H for each possible X. At the end, only the pair of decisions corresponding to the envelope's X is actually implemented (one decision from the CE task and one from the Machina task). This approach simplifies the design by ensuring that all instructions are provided upfront, avoids any follow-up randomization after the first part, and makes the link between the two parts transparent to participants. We follow Johnson et al. (2021) in referring to this approach as "PRINCE," but the main idea is simply to pre-commit to the random draw of X.

In the Machina task, Act L has ambiguity at the lower outcomes (0 and X) and a fixed payoff of \$100 if a red ball is drawn, whereas Act H has ambiguity at the higher outcomes (X and \$100) but can yield \$0 if a red ball is drawn. Participants check a box indicating which act they prefer, for each of the 21 possible values of X. After completing all choices, the envelope is opened to reveal the specific X. We then implement the corresponding choice from Part 1 and Part 2, using the same urn draws and lottery procedures described in Section 2. This yields a clean measure of whether Act L or Act H is chosen when the certain outcome is exactly the participant's own CE.

To familiarize subjects with PRINCE, we first used it for a first order stochastic dominance (FOSD) task (See Appendix A.1) and then for CE. Since the Machina experiment is implemented with the list method, we can explore if subjects have a unique switching point. A priori it is not clear that people have a unique switching point nor direction.

3.2. *Results*

In Part 1 (the "CE task"), each participant is given a list of possible cash amounts $X \in \{0, 1, \ldots, 20\}$. For each X, they must choose either "Receive \$X for sure" or "Play a 50–50 lottery for \$0/\$100." Crucially, participants may specify more precise (non-integer) values if desired—e.g., \$7.50—by writing them on the answer sheet. This PRINCE-based approach thus eliminates the need to force participants into pre-determined integer bins. In our dataset, 24 out of 91 participants (approximately 26%) reported a non-integer threshold.

After collecting these responses, we infer each participant's certainty equivalent (CE)—the point at which they switch from preferring the sure amount to the lottery. (If they write, say, \$7.50, that is recorded directly as their CE.) This CE then matters in Part 2 (the "Machina task"), where participants compare two ambiguous acts, L and H, at every $X \in$

$\{0, 1, \ldots, 20\}$. Importantly, before the experiment starts, each participant receives a sealed envelope that contains a randomly chosen integer X. Only after Part 2 is completed do we open the envelope: the revealed X determines (a) which sure-cash choice from Part 1 applies, and (b) which Act-L-vs.-Act-H choice from Part 2 is implemented.

Specifically, to test whether a subject is indifferent at their own CE, we observe which act they choose in Part 2 for the envelope's X. If this X equals (or is close to) a subject's self-reported CE, we can check whether they are indeed "indifferent" at that exact value. In cases where participants report a non-integer CE (e.g., $7.50), we look at their Part 2 choices for both $7 and $8 to see if their switch between L and H occurs in the interval [7,8]. This procedure ensures that all CEs—integer or not—are appropriately matched to the same scale used for the ambiguous acts. As we show below, most participants exhibit a clear preference in Part 2's ambiguous acts, rejecting the theoretical prediction that they would be indifferent exactly at their CE.

To visualize how far participants are from indifference at their own certainty equivalents (CE), Figure 1 plots each subject's CE on the x-axis and the switching point (S) on the y-axis. In each panel, the 45-degree line represents perfect alignment of CE $= S$. The sample includes people who always choose Act L or always choose Act H (coded as S=20) and those with a single switch. We display four different subsets in robustness checks, clockwise from the upper left: 1. All participants, 2. Participants with CE $\in [4, 10]$, 3. Participants who passed the First Order Stochastic Dominance (FOSD) test, and 4. Participants who satisfy both (2) and (3). ("Passed FOSD" means they consistently chose the stochastic-dominant option in a preliminary choice list.)

Visually, the vast majority of points in Figure 1 do not lie near the 45-degree line, indicating that for most individuals CE $\neq S$. A t-test strongly rejects the hypothesis that the mean of $|\text{CE} - S|$ is zero (t=7.8). Appendix B confirms this finding via a regression on "folded" data (i.e., absolute differences–to avoid averaging responses from subjects who switch above their CE with those who switch below their CE), showing that the confidence interval for the slope excludes 1. Together, these results reject the prediction of indifference at CE.

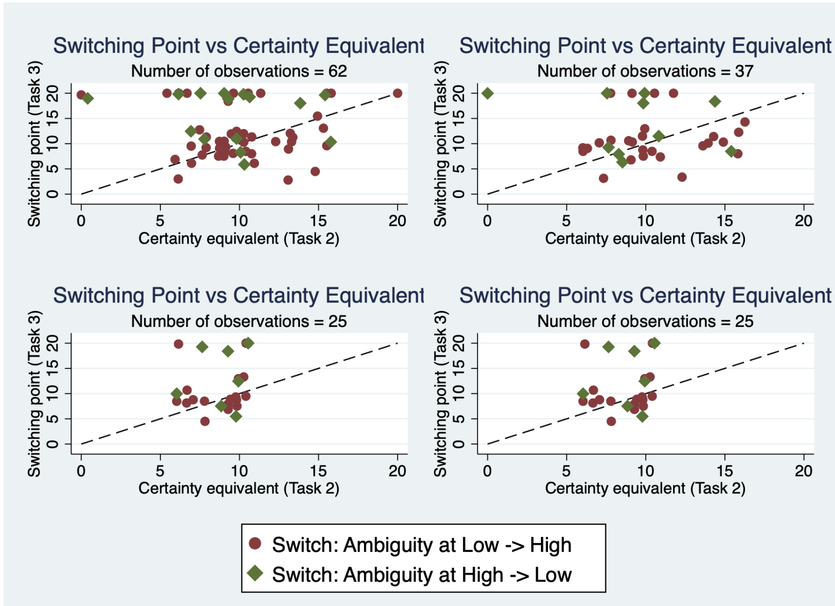

FIGURE 1.— CE vs. Switching point (raw data)

Notes: In each subplot, the 45 degree line is the $CE = S$ line. This sample includes people who always prefer L or always prefer H (their switching point is represented as 20) and people with single switching points. Each subplot presents a different sample in robustness checks. Clockwise from the upper left: (i) All participants, (ii) $CE \in [4, 10]$, (iii) FOSD, (iv) both.

Turning to explicit statements of indifference, we find that participants tend to prefer the act with ambiguity at the low outcome rather than at the high outcome. Figure 2 shows that only 13 of 91 subjects check "indifferent," and a binomial test rejects the hypothesis that everyone is indifferent (p<0.001). Next, we use each participant's switching point from our choice-list method in Part 2 to infer "indifference" more broadly. Figure 3 classifies participants as indifferent if they: 1. Explicitly report indifference at or near their CE (including up to two adjacent X values if they reported a non-integer CE), or 2. Have a clear switching point S that lies sufficiently close to their elicited CE when $\text{CE} \in [S - 1.96\,\text{SD}(\text{CE} - S), S + 1.96\,\text{SD}(\text{CE} - S)]$. The SD is calculated for $|\text{CE} - S|$ for the population, which biases against our results as this would tend to overestimate the number of people who are indifferent.

Here, S is defined as the midpoint between the last instance of choosing A over B and the first instance of choosing B over A. While this method potentially overestimates indifference by treating any small gap as "measurement error," the vast majority of participants still fail to qualify as indifferent under these generous criteria. Their CE values and switching points deviate noticeably, suggesting a genuine preference for one act.

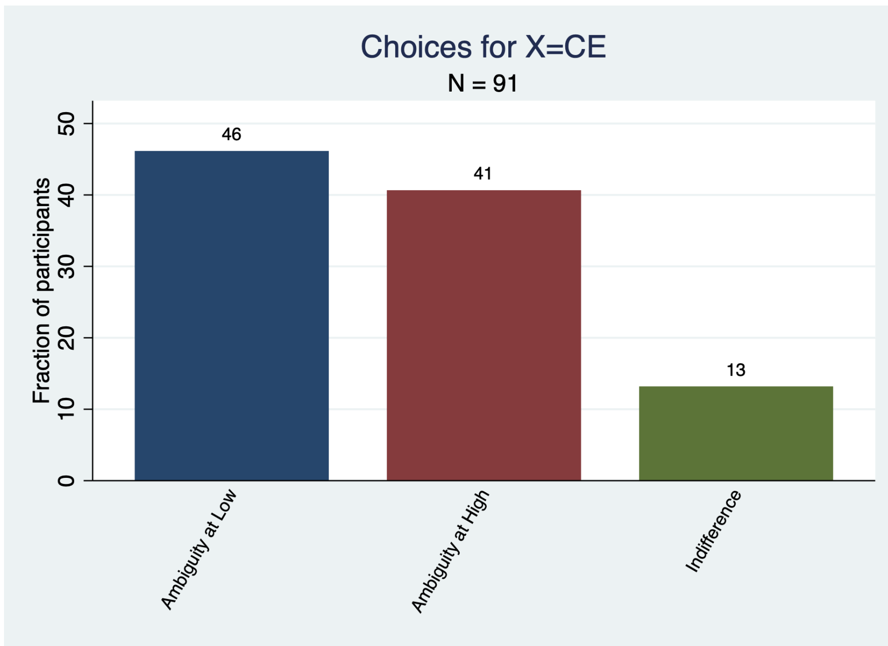

FIGURE 2.— All participants

Notes: Fraction of participants who choose ambiguity for the high outcome, ambiguity for the low outcome, or show indifference between the two options.

We also analyze switching behavior in more detail. We categorize participants into six types: (i) those who switch from Ambiguity-at-Low to Ambiguity-at-High, (ii) those who switch from Ambiguity-at-High to Ambiguity-at-Low, (iii) those who always choose Ambiguity-at-Low, (iv) those who always choose Ambiguity-at-High, (v) those who always declare indifference, and (vi) other: those with more complex (multiple) switching patterns. Three key findings emerge: 1. About one-fifth never switch at all, strictly preferring L or strictly preferring H. 2. Among switchers, most move from "ambiguity at low" to "ambiguity at high" as X increases—consistent with wanting to avoid ambiguity at higher payoffs. Even with reversed presentation order, a majority switch in that same direction. 3. Many participants' CE differs greatly from S, reinforcing that we can reject the Machina-based indifference at CE. A binomial test of the difference between the proportion of expressed indifference and 1 yields p=0.000. Appendix C provides further tabulations supporting this conclusion.

Overall, even allowing direct expressions of indifference and employing liberal criteria for classification, the data strongly reject the hypothesis that subjects are broadly indifferent between "ambiguity at low" and "ambiguity at high" outcomes.

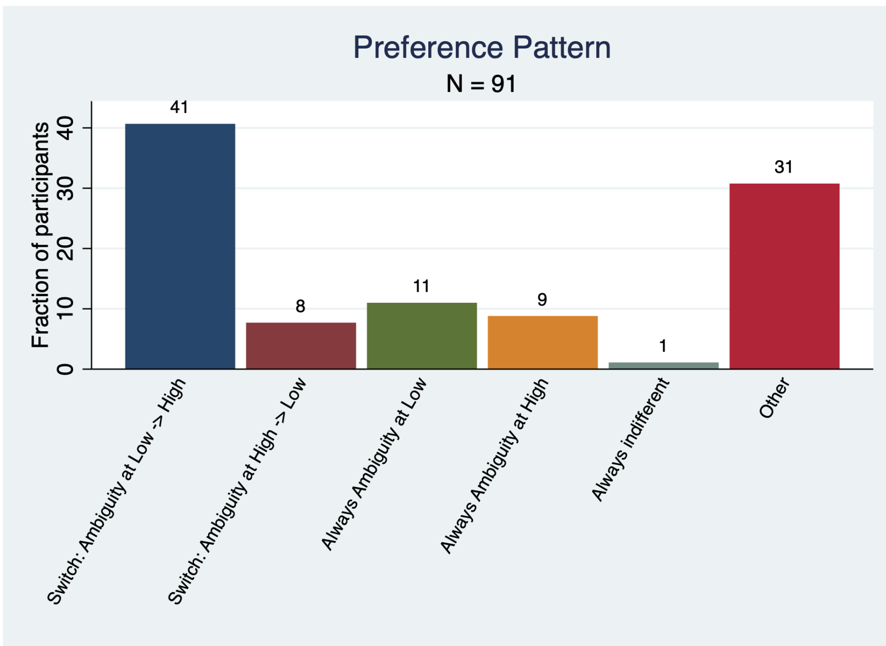

FIGURE 3.— All participants

Notes: Fraction of participants who choose to: (1) Switch from Ambiguity at Low to Ambiguity at High, (2) Switch from Ambiguity at High to Ambiguity at Low, (3) Always choose Ambiguity at Low, (4) Always choose Ambiguity at High, (5) Always remain indifferent, or (6) Other.

3.3. *Allais Consistency and Machina Behavior*

We now examine how participants' Allais consistency relates to their behavior in the Machina thought experiment. To do so, we presented two hypothetical questions modeled on the classic Allais paradox (see Appendix A). In these questions, each subject chose between:

- Lottery A: \$1 Million for sure

- Lottery B: 1% chance of \$0, 89% chance of \$1 Million, 10% chance of \$5 Million

and then:

- Lottery C: 89% chance of \$0, 11% chance of \$1 Million

- Lottery D: 90% chance of \$0, 10% chance of \$5 Million

Overall, these findings suggest that non–Allais-consistent participants—those who violate vNM independence—drive most of the observed departures from Machina's predicted indifference. Conversely, individuals who do not violate Allais behave more consistently with standard expected utility and therefore show indifference more often, as predicted by leading ambiguity-aversion models.

We also examine participants who pass a First-Order Stochastic Dominance (FOSD) check. Our data indicate that most FOSD passers—those who always choose the stochastically dominant lottery—also tend to be Allais consistent. Moreover, these FOSD passers/Allais-consistent participants are more likely to exhibit indifference in the Machina test, especially near their own certainty equivalent. This outcome matches our theoretical prediction that decision-makers who satisfy vNM independence (or something close to it) do not violate Machina-style indifference.

Hence, while only a subset of our sample passes both FOSD and Allais checks, these subjects align most strongly with the conventional prediction of indifference in Machina's "ambiguity-at-low-vs.-high" scenario. This underscores our interpretation that failing to be Allais consistent (and/or FOSD consistent) is the primary reason most participants do not exhibit Machina-style indifference.

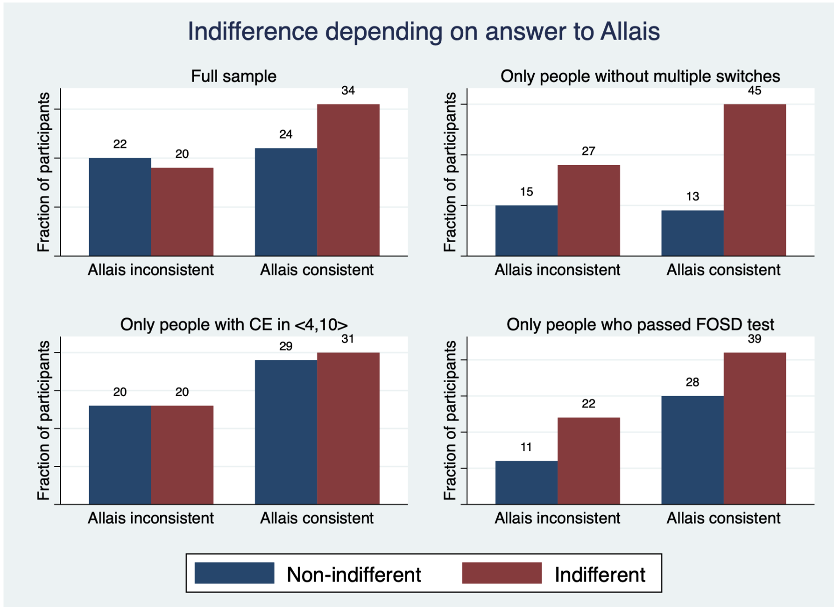

FIGURE 4.— Allais and Machina paradoxes

Notes: This figure displays the proportion of subjects who are categorized as indifferent. A subject is considered indifferent under two conditions: (1) They express indifference at their certainty equivalent (CE) or at two neighboring values. (2) They exhibit a clear switching point, with their CE falling within the confidence interval of this switching point. Each panel in the figure represents a sub-sample analysis, segmenting subjects based on their adherence to Allais consistency. Allais consistency is defined by whether subjects satisfy the vNM independence axiom. The sub-sample analyses are conducted as follows: (1) Full Sample: Includes all subjects. (2) No Multiple Switches: Includes only subjects who did not exhibit multiple switching points. (3) Passed FOSD Test: Includes only subjects who passed the First Order Stochastic Dominance (FOSD) test. (4) CE Range: Includes only subjects whose CE falls within a specified range of values.

4. CONCLUDING REMARKS

Our experiment implemented Machina's (2014) three-outcome thought experiment, in which four major theories of ambiguity aversion predict indifference between two ambiguous acts. Contrary to those predictions, we find that most participants strictly prefer one act over the other, signaling that these classical models do not fully capture behavior when ambiguity involves more than two possible outcomes. Notably, participants who do satisfy vNM independence (e.g., those who are Allais consistent or pass first-order stochastic dominance) are likelier to exhibit indifference, supporting the theoretical link between vNM independence and Machina's paradox.

This divergence between predicted and observed behavior has two major implications. First, it underscores that violations of vNM independence—rather than ambiguity aversion per se—may be the critical driver behind rejections of indifference. Ambiguity models grounded in vNM independence can be accurate only to the extent that decision-makers themselves adhere to that axiom. Second, our data provide empirical support for more flexible frameworks (e.g., disappointment aversion) that allow strict preference in Machina's scenario. These frameworks can accommodate decision-makers whose beliefs or risk attitudes differ at higher outcomes versus lower outcomes.

Looking ahead, further theoretical modeling should examine how alternative axioms or preference structures interact with vNM independence to produce deviations from classical predictions. Extending or refining models to capture non-independence, multi-stage ambiguities, or psychological factors (such as disappointment, regret, or other emotional responses) appears essential. Additionally, exploring broader forms of uncertainty—including those beyond classical Ellsberg-type setups—promises to deepen our understanding of how real-world decision-making departs from standard rational-choice benchmarks. Our findings thus highlight the importance of incorporating both institutional (e.g., multiple outcomes, uncertain states) and psychological (e.g., disappointment aversion) factors into the design of ambiguity theories and experiments.

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SUPPLEMENT TO TESTING AXIOMATIZATIONS OF AMBIGUITY AVERSION

Daniel L. Chen*

Abstract This supplementary appendix contains the calculations for the state-by-state disappointment averse utilities for acts L and H (Section A), the lab instructions (Section B) and additional analysis (Sections C and D).

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Online Appendix

Supplement to Testing Axiomatizations of Ambiguity Aversion

This supplementary appendix contains the calculations for the state-by-state disappointment averse utilities for acts L and H (Section A), the lab instructions (Section B) and additional analysis (Sections C and D).

A Machina's Three-Outcome Thought Experiment Under Disappointment Aversion

A.1 Gul's (1991) Disappointment Aversion Model Gul (1991) introduces a one-parameter model of *disappointment aversion* (DA), extending standard von Neumann–Morgenstern (vNM) expected utility. In this paper, we let the parameter $\beta > 0$ represent the *strength* of disappointment aversion. Under DA, the decision-maker penalizes "disappointing" outcomes (below the lottery's own certainty equivalent) more heavily, leading to a certainty equivalent V that is typically lower than the neutral expected utility. If $\beta = 0$, DA reduces to standard expected utility.For a 2-outcome lottery paying $\underline{x} < \overline{x}$ with probabilities $(p, 1-p)$, Gul's DA utility can be written:

$$v(\text{lottery}) = \frac{(1+\beta)\, p\, u(\underline{x}) + (1-p)\, u(\overline{x})}{1+\beta\, p},$$

where $u(\cdot)$ is the vNM utility of money. A higher $\beta > 0$ inflates the probability weight on the worse payoff, thus lowering v. When $\beta = 0$, we recover $(p\, u(\underline{x}) + (1-p)\, u(\overline{x}))$ as in standard EU.

A.2 Machina's Three-Outcome Acts. We have two acts (L and H) each yielding *conditional* lotteries in states BB, BW, WW. In Table 2, we list their outcome distributions plus each state's DA utility, assuming $u(0) = 0$, $u(100) = 100$, and $u(c) = 50$ under *neutral* labeling (since c is the midpoint in standard EU).

DA in a three-outcome lottery.

If only the *lowest* payoff $\underline{x}$ lies below the certainty equivalent, the DA formula generalizes to:

$$v(\underline{x},\ p;\ \overline{x},\ q;\ \text{mid},\ r) = \frac{(1+\beta)\, p\, u(\underline{x}) + q\, u(\overline{x}) + r\, u(\text{mid})}{1+\beta\, p},$$

with $p + q + r = 1$, $u(\underline{x}) < v < u(\text{mid}), u(\overline{x})$ etc. Then a bigger $\beta > 0$ lowers v by overweighting p.

A.3 Derivations for Table 2. Consider each state:

- *State BB, Act L*: a 2-outcome lottery $(2/3, 0;\ 1/3, 100)$. Plug into DA:

$$V_L(\text{BB}) = \frac{(1+\beta)\,(2/3)\, u(0) + (1/3)\, u(100)}{1+\beta\,(2/3)} = \frac{0 + 100/3}{1 + \frac{2}{3}\beta} = \frac{100}{3+2\beta}.$$

- *State BB, Act H*: a 2-outcome $(1/3, 0;\ 2/3, c)$. So

$$V_H(\text{BB}) = \frac{(1+\beta)\,(1/3)\, u(0) + (2/3)\, u(c)}{1+\beta\,(1/3)} = \frac{\frac{2}{3} \times 50}{1 + \frac{1}{3}\beta} = \frac{100/3}{(3+\beta)/3} = \frac{100}{3+\beta}.$$

- *State BW*: each act yields $(1/3, 0;\ 1/3, c;\ 1/3, 100)$, so

$$V_L(\mathrm{BW}) = V_H(\mathrm{BW}) = \frac{(1+\beta)\,(1/3)\,u(0) + (1/3)\,50 + (1/3)\,100}{1+\beta\,(1/3)} = \frac{150/3}{(3+\beta)/3} = \frac{150}{3+\beta}.$$

- *State WW, Act L*: a 2-outcome $(2/3, c;\ 1/3, 100)$ or a 3-outcome approach. Ultimately,

$$V_L(\mathrm{WW}) = \frac{(1+\beta)\,(2/3)\times 50 + (1/3)\times 100}{1+\beta\,(2/3)} = \frac{(2/3)(50+50\beta) + (1/3)\times 100}{1+\frac{2}{3}\beta}.$$

- *State WW, Act H*: $(1/3, 0;\ 2/3, 100)$, so

$$V_H(\mathrm{WW}) = \frac{(1+\beta)\,(1/3)\,0 + (2/3)\,100}{1+\beta\,(1/3)} = \frac{200/3}{(3+\beta)/3} = \frac{200}{3+\beta}.$$

Hence the final formulas appear as in Table 2.

A.4 Example: Preference Reversal. Under standard EU ($\beta = 0$), one typically finds $L \sim H$ or that their overall utility is the same if they have the same unconditional distribution. With $\beta > 0$, the DM *overweights* the chance of \$0. Depending on which act is likelier to yield that worst payoff in a crucial state, the DM may strictly prefer L or H. For instance, if the DM believes "BB" is highly probable, they might favor whichever act does *better* in BB state. That "better in BB" act is the one with a smaller chance of \$0. DA thus *breaks the indifference* predicted by standard EU, producing strict preferences consistent with Machina's paradox.

B Instructions For Lab Study

The first task is the first order stochastic dominance task. The second task is the CE task. The third task is the Machina task. The fourth task is a short survey questionnaire shown at the end.

B.1 First Order Stochastic Dominance Task Note that first order stochastic dominance implies that option B is always preferred when X is less than 7.

Option A	
Balls in drum	Money you get when a ball of this color is drawn
4 red balls	CHF X
3 white balls	CHF 9
3 black balls	CHF 7

Option B	
Balls in drum	Money you get when a ball of this color is drawn
2 red balls	CHF X
3 white balls	CHF 9
5 black balls	CHF 7

Figure 1: Envelope content - FOSD

□ If X is below or equal to CHF _ _, _ _ then I want **Option A**, else I will receive **Option B.**

□ If X is below or equal to CHF _ _, _ _ then I want **Option B**, else I will receive **Option A.**

Figure 2: Answer sheet - FOSD

B.2 Certainty Equivalent Task (PRINCE method)

Note that someone who is risk averse would write down X less than 10.

The drum is filled with 20 balls, 10 of which are white and 10 of which are black. The experimenter will draw one ball from the drum at random.

Option A
If the ball is black you get CHF 20. If the ball is white you get nothing.

Option B
Regardless of what color is drawn, you get **CHF X**.

Figure 3: Envelope content - CE

IF X is below or equal to CHF __ __,__ __ I want Option A, otherwise I will receive Option B.

Figure 4: Answer sheet - CE

B.3 Machina Task Note that someone who satisfies SEU would have a unique switching point when X is CE.

The ball will be drawn from a drum with 20 red balls and 40 balls which may be any combination of white and black balls. You do not know exactly how many white/black balls are in the drum. There are 60 balls in total in the drum. You can choose one of two options. The option payoff is dependent on the color of the ball drawn from the drum:

	20 balls	40 balls	
	Red ball drawn	Black ball drawn	White ball drawn
Option A	CHF 0	CHF **X**	CHF 20
Option B	CHF 20	CHF 0	CHF **X**

Figure 5: Envelope content - Machina

If X is....	...I want Option A	...I want Option B	I am indifferent
CHF 0			
CHF 1			
CHF 2			
CHF 3			
CHF 4			
CHF 5			
CHF 6			
CHF 7			
CHF 8			
CHF 9			
CHF 10			
CHF 11			
CHF 12			
CHF 13			
CHF 14			
CHF 15			
CHF 16			
CHF 17			
CHF 18			
CHF 19			
CHF 20			

Figure 6: Answer sheet - Machina

B.4 Complete Instructions For completeness, we include all relevant information seen by the subjects. The original colors for the experiment tasks are reproduced.

EXPERIMENT 1 **Participant number: _ _**

Please now enter your participant number in the space above.

In this first of 3 experiments you will decide between two options. In both options your payoff depends on the result of a random draw from a drum filled with balls and some unknown amount CHF X.

On the table in the middle of the room there is a drum. We will conduct 2 draws. First we will fill the drum as shown in the table "Option A" below and randomly draw a single ball. Then we will fill the drum as shown in the table for "Option B" below, and randomly draw a single ball.

When asked by the experimenter to do so, draw one sealed white envelope. Each participant will draw a white envelope. Each of these envelopes contains a note. The notes are identical except for the random value X which differs. The CHF X is a random number between CHF 0,00 and CHF 20,00. All possible numbers have equal probability.

The value of X is printed on the note inside the sealed envelope. You will only learn X once experiment 1 is over. Thus DO NOT OPEN YOUR ENVELOPE. It will be opened later by an experimenter in your presence. If you open your envelope yourself, you will not get paid for this experiment.

Here is what the note in each of the envelopes looks like:

Option A	
Balls in drum	Money you get when a ball of this color is drawn
4 red balls	CHF X
3 white balls	CHF 9
3 black balls	CHF 7

Option B	
Balls in drum	Money you get when a ball of this color is drawn
2 red balls	CHF X
3 white balls	CHF 9
5 black balls	CHF 7

You can choose whether you want to get Option A or Option B. But since your envelope may contain any value of X between 0,00 and 20,00 please give us general instructions whether you want Option A or Option B depending on the value of X.

Do so by selecting <u>**one**</u> of the following options and indicating a threshold:

□ If X is below or equal to CHF _ _, _ _ then I want **Option A**, else I will receive **Option B**.

□ If X is below or equal to CHF _ _, _ _ then I want **Option B**, else I will receive **Option A**.

Please give this sheet to the experimenter when asked to do so. He will later return it to you, and in the end you have to hand it to the cashier to get paid.

Figure 7: FOSD Task

EXPERIMENT 2 Participant number: _ _

Please now enter your participant number in the space above.

In this experiment you will decide whether you prefer to play a lottery, in which the payoff is dependent on the color of a ball randomly drawn from a drum, or to receive a guaranteed amount of money.

When asked by the experimenter to do so, draw one sealed green envelope. Each participant will draw a green envelope. Each of these envelopes contains a note. The notes are identical except for the random value X which differs. The CHF X is a random number between CHF 0,00 and CHF 20,00. All possible numbers have equal probability.

The value of X is printed on the note inside the sealed envelope. You will only learn X once experiment 2 is over. Thus DO NOT OPEN YOUR ENVELOPE. It will be opened later by an experimenter in your presence. If you open your envelope yourself, you will not get paid for this experiment.

In this experiment 2 the note has two options: participating in the lottery or receiving a guaranteed amount of money. The guaranteed amount of money is CHF X.

Here is what the note in each of the envelopes looks like:

> The drum is filled with 20 balls, 10 of which are white and 10 of which are black. The experimenter will draw one ball from the drum at random.
>
> **Option A**
> If the ball is black you get CHF 20. If the ball is white you get nothing.
>
> **Option B**
> Regardless of what color is drawn, you get **CHF X**.

Since your envelope may contain any value of X between 0,00 and 20,00 please give us general instructions whether you want Option A or Option B. Do so by specifying a threshold:

IF X is below or equal to CHF _ _,_ _ I want Option A, otherwise I will receive Option B.

Please give this sheet to the experimenter when asked to do so. He will later return it to you, and in the end you have to hand it to the cashier to get paid.

Figure 8: CE Task

EXPERIMENT 3 **Participant number: _ _**

Please now enter your participant number in the space above.

In experiment 3 you will choose one of two options. In both options your payoff depends on the result of a random draw from a drum filled with balls and some unknown amount CHF X.

On the table in the middle of the room there is a drum. We will conduct a single draw. The experimenter will show you the drum with 20 red balls already in it. He will also show you a box with 40 white balls, and a box with 40 black balls. Later, in secret he will add exactly 40 white and black balls to the drum in addition to the 20 red ones already in the drum. The additional 40 balls may be any combination of black and white balls. The experimenter could for example add 7 black balls and 33 white balls or just add 40 white balls, or he could add 12 white balls and 28 black balls, or.... He can do whatever he likes as long as the sum of white and black balls in the drum is exactly 40, and the number of red balls in the drum remains at 20.

When asked by the experimenter to do so, draw one sealed blue envelope. Each participant will draw a blue envelope. Each of these envelopes contains a note. The notes are identical except for the random value X which differs. The CHF X is a random number between CHF 0 and CHF 20. In this experiment these numbers will be only whole Swiss Francs, so CHF 0, CHF 1, CHF 2,............, CHF 19, CHF 20. Thus there are 21 possible numbers, and they have equal probability.

The value of X is printed on the note inside the sealed envelope. You will only learn X once experiment 3 is over. Thus DO NOT OPEN YOUR ENVELOPE. It will be opened later by an experimenter in your presence. If you open your envelope yourself, you will not get paid for this experiment.

Here is what the note in each of the envelopes looks like:

The ball will be drawn from a drum with 20 red balls and 40 balls which may be any combination of white and black balls. You do not know exactly how many white/black balls are in the drum. There are 60 balls in total in the drum. You can choose one of two options. The option payoff is dependent on the color of the ball drawn from the drum:

	20 balls	40 balls	
	Red ball drawn	Black ball drawn	White ball drawn
Option A	CHF 20	CHF 0	CHF X
Option B	CHF 0	CHF X	CHF 20

PLEASE NOW ANSWER THE QUESTIONS ON THE OTHER SIDE OF THIS PAPER

Figure 9: Machina Task (page 1)

Please give us instructions, for each possible value of X that your envelope may contain, whether you want Option A or B. Do so by ticking the option you prefer for every possible value of X (so put exactly one tick in each of the 21 rows). If you are indifferent, you will get the payoff from Option A or Option B – it will be randomly determined which one.

If X is....	...I want Option A	...I want Option B	I am indifferent
CHF 0			
CHF 1			
CHF 2			
CHF 3			
CHF 4			
CHF 5			
CHF 6			
CHF 7			
CHF 8			
CHF 9			
CHF 10			
CHF 11			
CHF 12			
CHF 13			
CHF 14			
CHF 15			
CHF 16			
CHF 17			
CHF 18			
CHF 19			
CHF 20			

Note: This question does not have a "correct" answer. So just think row by row which option you feel is better.

Please give this sheet to the experimenter when asked to do so.
He will later return it to you, and in the end you have to hand it to the cashier to get paid.

Figure 10: Machina Task (page 2)

QUESTIONNAIRE **Participant number:___**

Please now enter your participant number in the space above

Please answer the following questions.

QUESTIONNAIRE PART 1

A doctor gives you 3 pills, and tell you to take 1 pill every 30 minutes starting right away. After how many minutes will you run out of pills? ____________minutes

A meal, including a beverage costs CHF 12 in total. The food costs 5 times as much as the beverage. How much does the food cost? _________

A population of a town halves every month due to a plague. 1 000 people are still alive after 10 months. After how many months were 2 000 people alive? _________

QUESTIONNAIRE PART 2

In this part of the questionnaire we will ask you to make a choice between pairs of lotteries. These lotteries will NOT be paid out. Please answer as you think you would if the choice were real rather than hypothetical. Note that in neither of these questions there is a unique correct answer.

QUESTION: Suppose you got offered a choice between these 2 lotteries. Suppose you would not have to pay anything for either of them, and you could choose exactly one lottery.
Which one would you choose?

O Lottery A: CHF 1 Million for sure

O Lottery B: 1% Chance of Nothing.
89% Chance of CHF 1 Million.
10% Chance of CHF 5 Million

Figure 11: Questionnaire (page 1)

QUESTION: Now imagine you did not get the choice offered above, but instead got offered a choice between the 2 lotteries below for free. Suppose you got offered a choice between these 2 lotteries for free. And you could choose exactly one.
Which one would you choose?

O Lottery C: 89% Chance of Nothing
11% Chance of 1 Million CHF

O Lottery D: 90% Chance of Nothing.
10% Chance of 5 Million CHF

QUESTIONNAIRE PART 3

1. What is your country of citizenship: ______________________________

2. What is your mother tongue (native language): ______________________________

3. What is your age? ______years

4. What is your gender? O Male O Female

5. In what kind of program are you currently enrolled?

O Bachelor's program O Master's program O Not a student

6. In which year do you think you will graduate from your current program?

O 2014 O 2015 O 2016 O 2017 O 2018 O Later O I am not a student.

7. What is your field of study? ______________________________

8. Have many times have you participated in experiments before today (in this ETH laboratory or at the University of Zurich) ?

O Never O Once O 2times O 3 times O ______

9. How hard to understand were today's experiments? For each experiment choose the most appropriate option. Please note that this will not influence your payoff and will not be linked to your personal data.

	I didn't understand the instructions	I understood the instructions, but I didn't know what answer to give	Everything was clear	Other (provide extra details)
Experiment 1				
Experiment 2				
Experiment 3				

Figure 12: Questionnaire (page 2)

C Additional Regression Analysis of CE and Switching Points

This figure visualizes a regression line and replaces the some dots with bars when subjects report indifference for a range rather than the data indicating a switching point. On this evidence, the confidence interval for the regression line excludes the 45 degree line for the entire set of participants. Smaller samples of the data, however, would not reject the null.

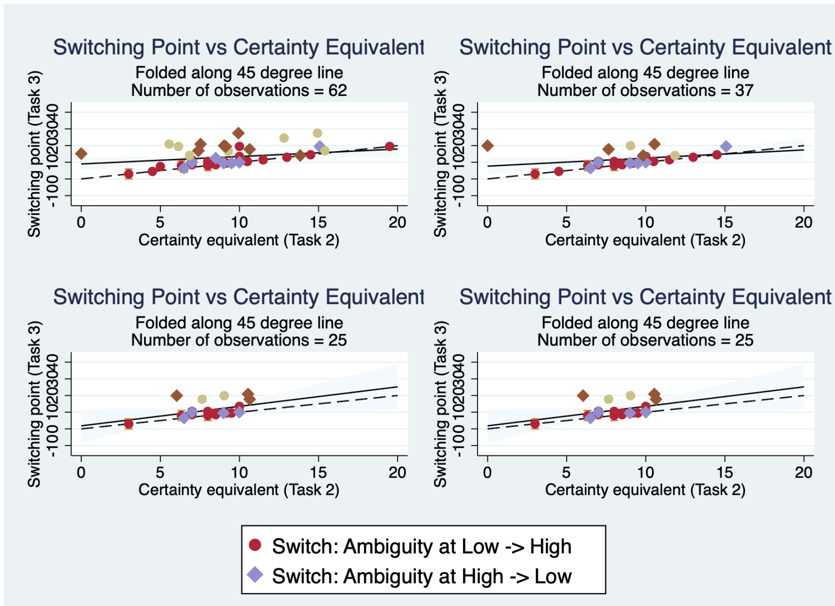

Figure 13: CE vs. Switching point (folded, with regression line)

Notes: This figure is the analog to Figure 1, except that the data is "folded" around the 45-degree line to avoid averaging responses from subjects who switch above their CE with those who switch below their CE. The figure presents the CE on the x-axis and the “folded” switching point on the y-axis. The 45-degree line (CE = S line) indicates indifference. Each subplot presents a different sample for robustness checks, arranged clockwise from the upper left: (i) all participants, (ii) CE $\in$ [4, 10], (iii) FOSD, and (iv) both.

D Additional Analyses

D.1 Switching Points Next, we restrict to participants with a certainty equivalent between 4 and 10, inclusive. The results are similar as without the restriction.

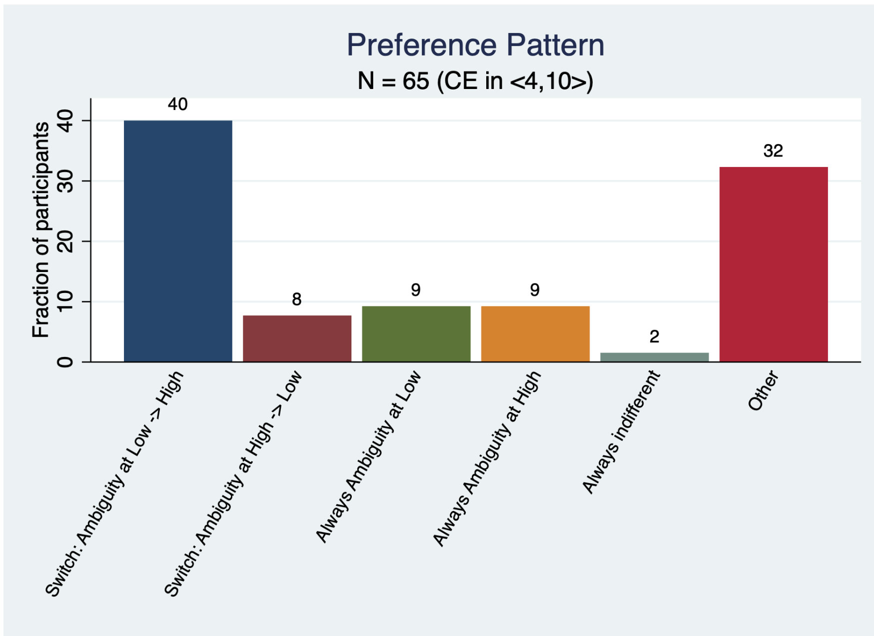

Figure 14: Participants with reasonable CE

Notes: Fraction of participants with a Certainty Equivalent in the range of 4-10 who choose to: (1) Switch from Ambiguity at Low to Ambiguity at High, (2) Switch from Ambiguity at High to Ambiguity at Low, (3) Always choose Ambiguity at Low, (4) Always choose Ambiguity at High, (5) Always remain indifferent, or (6) Other.

The following tabulation indicates there exists many people for whom CE strongly differs from S:

	Count	Share in %
CE inside switch interval	20	46.5
CE outside switch interval	23	53.5
Total	43	100

Figure 15: Whether CE is inside Machina switching point interval

We also present the number of observations for specific combinations of CE and S values:

	CE<10	CE=10	CE>10
S<10	14	4	4
S=10	1	1	0
S>10	5	6	9

Figure 16: 2x2 table of CE vs. Switching point

D.2 Order Effects The order of the lottery presentation was randomized, but we can check if the order influenced the switch direction. We find that the answer is yes, but people still generally switch from Ambiguity at Low to Ambiguity at High.

Fraction of switches from Risk at Low Outcome to Risk at High Outcome depending on the order of options on the answer sheet (normal order lists Risk at High Outcome first).

Group	Obs	Mean	Std Dev
Normal Order	32	.13	.34
Reversed order	11	.18	.4

H0: means are equal; p-value for two-sided test: 0.648

Figure 17: Order and switch direction

The tabulation indicates that the fraction of switches from Ambiguity at High to Ambiguity at Low depends on the order of options on the answer sheet (normal order lists Ambiguity at Low Outcome first). But even with the reversed order, the majority of subjects switch from Ambiguity at Low to Ambiguity at High.