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# Savage vs. Anscombe-Aumann: An experimental investigation of ambiguity frameworks

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# Savage vs. Anscombe-Aumann: An experimental investigation of ambiguity frameworks*

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**Abstract**

The Savage and the Anscombe-Aumann frameworks are the two most popular approaches used when modeling ambiguity. The former is more flexible, but the latter is often preferred for its simplicity. We conduct an experiment where subjects place bets on the joint outcome of an ambiguous urn and a fair coin. We document that more than a third of our subjects make choices that are incompatible with Anscombe-Aumann for any preferences, while the Savage framework is flexible enough to account for subjects' behaviors.

**JEL codes:** C91; C72; D74.
**Keywords:** Ellsberg paradox, ambiguity, experiment.

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# 1 Introduction

The Savage (1954) and the Anscombe-Aumann (1963) frameworks are the two most popular approaches when it comes to modelling ambiguity. The latter is a two-stage model where acts are maps from states to objective lotteries over consequences. It is often preferred for its simplicity, but the Savage model provides more flexibility. Gilboa and Schmeidler (1989) and Schmeidler (1989) used the Anscombe and Aumann approach as a basis for their seminal contributions to ambiguity theory. Eichberger and Kelsey (1996) show that, for standard ambiguity models like Choquet expected utility (CEU) and Maxmin Expected Utility, ambiguity aversion implies a strict preference for randomization when looked at in the Anscombe-Aumann framework. They also show that the same need not hold in the Savage framework. Eichberger and Kelsey (1996) argue against the plausibility of a general preference for randomization but also admit the need for further experiments on this question.[1]

We implement an experiment in which some choices are inconsistent with ambiguity models that are based on the preference framework of Anscombe and Aumann (1963). We show that these choices can be consistent within a Savage framework using e.g. a CEU model as in Eichberger and Kelsey (1996). The experiment involves subjects choosing from among six options that each relate to the outcomes of a coin flip and a draw from an ambiguous, 2-color urn. Two of the six options result in a clearly ambiguous act. Two more of the six options result in a clearly risky act. The last two options would be considered risky acts within the Anscombe-Aumann framework, but would be treated as ambiguous acts within the Savage framework. By manipulating the payoffs within the various acts, we are able to create a dominance relationship between the four risky acts using the Anscombe-Aumann framework. We find that dominated acts are still chosen by subjects more than a third of the time. The same subject choices can be explained with ambiguity models using the Savage framework, where the dominance relationship does not necessarily hold.

The two acts that highlight the differences between the two frameworks involve ambiguity hedging (see Oechssler and Roomets, 2014, and Oechssler et al. 2019). These acts are akin to betting on one color when a coin flip comes up heads, and a different color when the coin flip comes up tails. Within the Anscombe Aumann framework, subjects

[1] In the meantime a number of experiments (see in particular, Dominiak and Schnedler, 2011, and Oechssler, Rau, and Roomets, 2019) have shown that indeed few subjects have a strict preferences for randomization.

making such a combination exploit the complementarity of the probabilities of the two colors of balls in the urn to arrive at a believed 50:50 chance to win the bet. Within the Savage framework, such complementarity need not be assumed. Subjects are allowed to believe that the probabilities of the two colors depend on the coin flip. So, when a subject considers choosing an act that combines bets on blue (when the coins shows heads) and yellow (when the coin shows tails), the subject could believe that blue is unlikely when the coin shows heads and also that yellow is unlikely when the coin shows tails. Therefore, while the hedge acts represent risk using the Anscombe-Aumann framework, the same acts represent ambiguity using the Savage framework.

While it may seem we are pitting one framework against the other in a "mano-a-mano" bout, we caution readers that the way we have been able to design choices leaves Savage mostly out of harms way while placing Anscombe and Aumann in jeopardy. Some may point out that the flexibility of the Savage framework is what keeps it out of the fray, and that this flexibility should be considered an advantage. We can not disagree, but we leave discussions of the relative flexibility of the frameworks to more theoretical papers. As a fundamentally experimental endeavor, this paper should be viewed primarily as a test of the Anscombe-Aumann framework. Our results are not supportive of the Anscombe-Aumann framework in this context. This represents our main finding and contribution. It is, of course, interesting that the Savage framework could have explained our subjects' behavior when the Anscombe-Aumann framework could not. However, this should not be considered direct support for the Savage framework as there was no way it could have failed in our experimental setting.

## 2 Experimental design

The experiment consisted of a single incentivized task,[2] followed by an unincentivized questionnaire. Subject had to choose one of the six acts that depended on the outcome of a fair coin and the outcome of a draw from an Ellsberg urn.[3] The urn contained 24 blue and yellow balls in a composition that was unknown to subjects. Subjects were told that any combination from 0 blue balls (and 24 yellow balls) to 24 blue balls (and 0 yellow balls) was possible. In treatment A, subjects chose from the six acts listed in Table 1. In

[2] Having several tasks with some probabilistic or fixed payment rule would run the risk of confounding ambiguity with hedging motives or with attitudes towards compound lotteries (see e.g. Halevy, 2007).

[3] In the actual experiment, we used a non-transparent bag and blue and yellow marbles. For expositional reasons, we employ the more customary urns and balls in the text.

treatment B the payoffs of \$21 and \$22 were interchanged, while all other design aspects were kept constant. The payoffs were chosen so as to act as a tie-breaker for subjects who thought that some or all states are equally likely and to create the aforementioned dominance relationship within the Anscombe-Aumann framework.

Table 1: Acts and payoffs

| acts | coin shows heads | | coin shows tails | |
|---|---|---|---|---|
| | ball blue | ball yellow | ball blue | ball yellow |
| | $s_1$ | $s_2$ | $s_3$ | $s_4$ |
| "blue" ($bb$) | \$21 | \$0 | \$21 | \$0 |
| "yellow" ($yy$) | \$0 | \$21 | \$0 | \$21 |
| "heads" ($h$) | \$20 | \$20 | \$0 | \$0 |
| "tails" ($t$) | \$0 | \$0\$ | \$20 | \$20 |
| "hedge by" ($by$) | \$22 | \$0 | \$0 | \$22 |
| "hedge yb" ($yb$) | \$0 | \$22 | \$22 | \$0 |

In the experiment, the acts were labeled neutrally "Option A" through "Option F" and were presented in a random order. Here we have given them names that highlight their nature. The "heads" act, for example, will win if the coin shows heads, regardless of the ball draw. The "hedge yb" act would win if the ball drawn is yellow and the coin shows "heads" or if the ball drawn is blue and the coin shows "tails".

At the end of the experiment, subject volunteers drew a ball from the urn and tossed the fair coin. Importantly, the ball was drawn first (and shown to subjects), then the coin was tossed.[4] This timing was explained in the instructions.

After the acts were chosen, but before the random variables were determined, subjects filled out a questionnaire. The questionnaire included unincentivized questions about how subjects chose their bet in the elicitation task, a hypothetical three-color Ellsberg experiment, demographics, a hypothetical two-color Ellsberg urn, and beliefs about the random variables in the elicitation task (see the appendix for the questionnaire).

Experiments were conducted using pen and paper at the Economics Science Laboratory at the University of Arizona. Subjects were students at the university. There were 93 subjects in treatment A (57% female) and 31 subjects in treatment B (48% female). The experiment took roughly 30 minutes, and subjects received an average of \$19.91 including

[4]This was done so that we did not need to rely on the reversal-of-order axiom (see Anscombe and Aumann, 1963).

a \$10 show-up fee. Decisions and payments were made privately (with respect to other subjects).

Instructions (see Appendix) were distributed on paper and read aloud at the beginning of the experiment. Urns were on display during the entire experiment, so that subjects could be certain that the urns' contents could not be manipulated. Subjects were allowed to verify the urns' contents after the experiment, and some did.

## 3 Hypotheses

The two standard approaches to model uncertainty, the Anscombe and Aumann (1963) and the Savage (1954) framework, differ in the way they model a randomization device like a fair coin (see e.g. Eichberger and Kelsey, 1996, or Klibanoff, 2004). In the Savage framework, the outcomes of a randomizing device must be modelled explicitly as part of the description of a state. The state space is the Cartesian product $S_S = U \times R$, where $U = \{b, y\}$ is the outcome of the draw from an urn (ambiguous) and $R = \{H, T\}$ is the outcome of a fair coin flip (objective randomization device). Hence, e.g. $s_1 = bH$ denotes the state where the drawn ball was blue and the coin flip produced heads. Thus, in our experiment we have the state space $S = \{s_1, ...s_4\}$ listed in Table 1 and a finite set of consequences $X = \{0, 20, 21, 22\}$. An act is a map $f : S_S \to X$ and preferences are defined as binary relations on $\mathcal{F}$, the set of all acts.

In the experiment there were the six acts listed in Table 1. Figure 1 illustrates the three types of acts available, the "hedge" acts $(by, yb)$, the "color" acts $(bb, yy)$, and the "coin" acts $(h, t)$. The tree to the left shows the "hedge by" act, the tree in center shows the act "blue", and the tree to the right shows the act "heads".[5]

In the Anscombe-Aumann framework, randomization devices are incorporated into the consequence space. The state space would consist only of $S_{AA} = \{b, y\}$. Consequences would be all simple lotteries (probability distributions) on $X$, denoted by $\Delta(X)$. Acts in the Anscombe-Aumann world are maps $f : S \to \Delta(X)$ and are listed in Table 2.

The crucial thing to note is that in an Anscombe and Aumann framework, both the "hedge" acts and the "coin" acts yield objective 50:50 lotteries. However, the hedge acts yield lotteries that pay out \$22 (\$21 in Treatment B) when successful while the coin acts only pay out \$20. Thus, any decision maker should strictly prefer either of the hedge acts

[5] The remaining three acts are the mirror images of these three acts.

Table 2: Acts and payoffs in Anscombe-Aumann

| | ball blue $s_1$ | ball yellow $s_2$ |
|---|---|---|
| hedge acts $(by, yb)$ | $\frac{1}{2}\$22 + \frac{1}{2}\$0$ | $\frac{1}{2}\$22 + \frac{1}{2}\$0$ |
| coin acts $(h, t)$ | $\frac{1}{2}\$20 + \frac{1}{2}\$0$ | $\frac{1}{2}\$20 + \frac{1}{2}\$0$ |
| color act $yy$ | \$0 | \$21 |
| color act $bb$ | \$21 | \$0 |

Note: In treatment B the payoffs \$22 and \$21 are reversed.

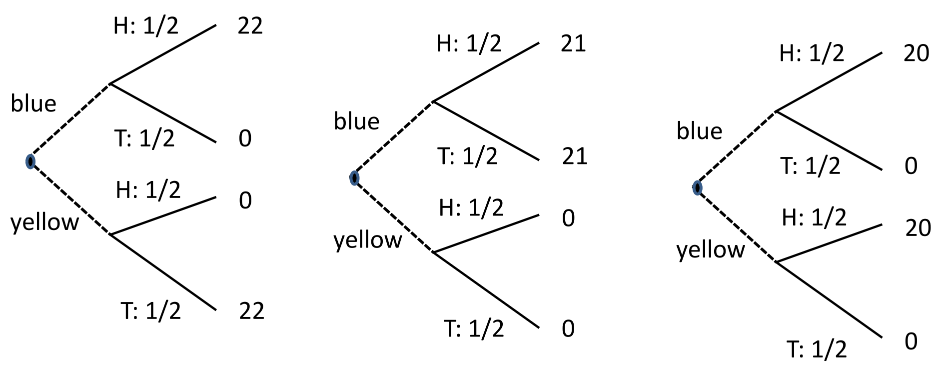


Figure 1: An illustration of a "hedge" act (left), a "color" act (center), and a "coin" act (right).

to the coin acts.[6]

**Hypothesis** In the Anscombe-Aumann framework, no decision maker should choose a coin act in either of the treatments.

This hypothesis need not hold in a Savage framework (see Eichberger and Kelsey, 1996). To construct a counter-example, consider a Choquet-Expected Utility (CEU) maximizer with the following capacity $v(\cdot)$ and linear utility function $u$,

[6] Furthermore, in Treatment A, any ambiguity averse decision maker with symmetric priors should strictly prefer the hedge acts to the color acts.

$$\begin{aligned} M &\subseteq N \Rightarrow v(M) \leq v(N) \\ v(\varnothing) &= 0 \\ v(S) &= 1. \end{aligned}$$

It is permissible to assume (see Assumption 3.1 in Eichberger and Kelsey, 1996) that

$$\text{for all } M \subseteq R, v(M \times U) = p(M),$$

where $p$ is the additive probability distribution of the randomization device (in our case, $p(H) = p(T) = \frac{1}{2}$). Intuitively, the capacity on $S$ respects the probability of the coin flip for events that exclusively depend on the outcome of the coin flip. Under this assumption, $v(\{s_1, s_2\}) = v(\{s_3, s_4\}) = 0.5$ and, therefore, coin acts are not ambiguous.

Now suppose that $v(\{s_i\}) = 0.1, \forall i$, and $v(\{s_1, s_3\}) = v(\{s_1, s_4\}) = v(\{s_2, s_3\}) = v(\{s_2, s_4\}) = 0.4$. In this case,

$$CEU(h) = 0.5u(20) = 10 > 0.4u(22) = 8.8 \geq CEU(f),$$

for all non-coin acts $f$.[7] Thus, a CEU maximizer need not satisfy the above hypothesis.

# 4 Results

Subjects decisions in our experiment are presented in Table 3. The left hand side presents how many subjects chose the various acts, while the right hand side combines acts of the same type and includes the percent of subjects choosing each type of act. The most important thing to notice is that there are many more coin act decisions than our main hypothesis would suggest. In fact, coin acts were the most popular choice when combining the data from both treatments. Statistically, this is a clear rejection of our main hypothesis. However, this hypothesis is very strict in that a single coin act could be used to justify rejection. So, it is worth considering whether coin acts could plausibly be explained as mistakes. If coin acts are a result of mistakes by subjects otherwise consistent with the Anscombe-Aumann framework, this would mean that (by a conservative estimate) around 1/3 of subjects made mistakes in our experiment. However, it would be more reasonable to assume that mistakes were randomly distributed over the choices subjects did not intend to

[7] The inequality is due to the different payoffs in treatment A and B.

make. Since the coin acts represent only 2/5 of possible mistakes subjects could make in our design, a more realistic estimate of the percentage of mistakes is roughly 5/6 of subjects. We believe that it is unlikely that 5/6 of our subjects made mistakes when indicating their preferred act, and so we view our results as a strong rejection of our main hypothesis, even when allowing for some measurement error.

Table 3: Decision results by treatment

| Decision | Treatment | | Total | Type | | Treatment | | Total |
|---|---|---|---|---|---|---|---|---|
| | A | B | | | | A | B | |
| *bb* | 11 | 10 | 21 | Color acts | Count | 24 | 15 | 39 |
| *yy* | 13 | 5 | 18 | | Percent | 25.8% | 48.4% | 31.5% |
| *h* | 19 | 5 | 24 | Coin acts | Count | 34 | 9 | 43 |
| *t* | 15 | 4 | 19 | | Percent | 36.6% | 29.0% | 34.7% |
| *by* | 19 | 3 | 22 | Hedge acts | Count | 35 | 7 | 42 |
| *yb* | 16 | 4 | 20 | | Percent | 37.6% | 22.6% | 33.9% |
| Total | 93 | 31 | 124 | Total | | 93 | 31 | 124 |

### 4.1 Who chose the coin acts?

While our main hypothesis and results concern the proportion of subjects that chose the various acts, we can also employ the questionnaire data in order to help explain why certain acts were chosen. For example, we look at what might have led subjects to choose a coin act, which is inconsistent with the Anscombe-Aumann framework. For each type of act, we estimate a linear probability model with a left-hand-side variable equal to "1" if the subject bet on that type of act and equal to "0" otherwise.[8] For explanatory variables, we use ambiguity attitude as measured separately by hypothetical 2- and 3-color Ellsberg urn questions in the questionnaire. We then use data from a written explanation of the original incentivized decision, which we asked for in the questionnaire.[9] We also use a treatment dummy and a treatment dummy interacted with a questionnaire response related to payoff comparisons. The interaction term is included because the ranking of payoffs differs across treatments.

In order to translate subjects' written explanations into a usable format, we employed

[8] Logit and probit models yield similar conclusions.

[9] We asked subjects the following question immediately after choosing their incentivized bets and gave them a full page to respond: "What was your thought process when you made your decision?"

three additional student coders who were asked to read through the questionnaire responses and identify whether certain topics were discussed. The topics included the relative "risk / safety" and "known / unknown likelihood" of the different options, the idea that all options are equally likely, the relative payoffs of different options, and others.[10] These student coders entered a "1" if a topic was discussed, and a "0" otherwise. The three codings were averaged to create our final measure of topics discussed, which we use in our regressions. Regression results are available in Table 4.

Table 4: Regressions of questionnaire responses
Probability of choices

| | Act Type | | |
|---|---|---|---|
| Variable | Color | Coin | Hedge |
| Ambiguity Averse | −0.208** | 0.195** | 0.013 |
| (3 Color) | (0.082) | (0.079) | (0.073) |
| Ambiguity Averse | −0.210* | 0.164 | 0.046 |
| (2 Color) | (0.117) | (0.112) | (0.105) |
| Risk / Safety | −0.137 | 0.409*** | −0.272** |
| | (0.131) | (0.125) | (0.117) |
| Known / Unknown | −0.113 | 0.423*** | −0.310*** |
| | (0.104) | (0.100) | (0.093) |
| Equally Likely | −0.104 | −0.421*** | 0.525*** |
| | (0.130) | (0.125) | (0.116) |
| Relative Payoffs | −0.227** | −0.125 | 0.353*** |
| | (0.106) | (0.101) | (0.094) |
| Treatment | 0.124 | −0.254** | 0.131 |
| (Treatment B = 1) | (0.111) | (0.107) | (0.099) |
| Relative Payoff × Treatment | 0.273 | 0.152 | −0.425** |
| | (0.227) | (0.217) | (0.202) |
| constant | 0.647*** | 0.167 | 0.186 |
| | (0.187) | (0.179) | (0.167) |
| N | 124 | 124 | 124 |
| Adjusted $R^2$ | 0.156 | 0.263 | 0.353 |

*,**,*** - Significant at the 10%, 5%, 1% level respectively. Standard errors in parentheses.

We find that choosing a coin act seemed to be preferred by subjects that expressed

[10] A full list of topics and the instructions given to the student coders is available as an appendix. Coders had access to the experimenters while working in order to ask clarifying questions about the topics, but the experimenters declined to answer questions about how to code specific responses.

ambiguity averse preferences in the hypothetical 3-color urn question,[11] cited the relative risk and/or the relatively known likelihoods of various outcomes, and did not comment on all outcomes being equally likely. Relative payoff discussion is negatively correlated to choosing coin acts (which had the lowest expected payoff) but not significantly so.

As one might suspect, choosing a color act was negatively correlated to ambiguity aversion measures (both 3-color and 2-color measures). Choosing a color act was also negatively correlated with the discussion of payoff differences in treatment A, when "Hedge betting" had the highest winning payoff. In treatment B, when the color acts had the highest winning payoff, this effect is cancelled out.

Choosing a hedge act seemed to be preferred by subjects that discussed that acts were equally likely, and focused on payoff differences. This led to much more frequent hedge act choices in treatment A, where the hedge acts had the highest winning payoff. Unlike what would be expected according to theory, choosing hedge acts did not appear particularly related to ambiguity aversion.

## 5 Conclusion

Based on our hypothesis, subjects in our experiment should not have chosen coin acts according to the Anscombe-Aumann framework. However, more than 1/3 of our subjects did. Given that coin acts made up precisely 1/3 of the options available to subjects, attributing these choices to measurement error would imply that practically all subjects erred in their selection or were indifferent between options (despite the payoff asymmetry). The latter seems particularly unlikely given the results from the questionnaire that evidence a sensible pattern of preferences; Ambiguity averse subjects chose the coin acts more often than ambiguity neutral/loving subjects. So, we are left to assume that subjects expressed a meaningful preference for the coin acts, contradicting our hypothesis. Many subjects, it seems, did not view both the coin and hedge acts as 50/50 propositions, or, if they did, there was some other factor that affected preferences but was not modeled. Either way, models using the Anscombe-Aumann framework were unable to correctly explain a large portion of subject decisions in our setting.

While it may seem then that we are left endorsing the Savage framework, we stop short of such an endorsement. While we do not find violations within the choice data, since any

[11] Preferences with respect to the 2-color urn were positively correlated with coin acts, but this relationship was not significant.

choice is plausibly supported in the Savage framework, neither do we find positive support for the framework in subjects' written explanations of their act choices. When asked to explain the act they chose, fewer than 5% of subjects were coded as having discussed the combined outcomes that make up the state space in the Savage framework. Instead, subjects tended to reference the coin flip and the ball draw independently. Of course, subjects need not express the particulars of a framework in writing in order to employ that framework in their decision making. Therefore, we see our results as neutral with respect to the Savage framework, and leave the door open to the possibility that subjects adhere to a framework we failed to consider in this paper.

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## Appendix (for online publication only)

# Experimental Instructions

Welcome to our experiment and thank you for participating!

From now on, please don't talk to your neighbors and turn off your mobile phone. If you have any questions, please raise your hand, and someone will come over and will answer the question for you.

All participants who observe the rules will definitely receive a guaranteed $10. Furthermore, you have the chance to receive more. Whether you receive an additional amount depends on your decisions and the outcome of a lottery. At the end of the experiment you will receive your total payment in cash and anonymously.

On the table of the experimenters we have a bag containing 24 marbles which are either blue or yellow. The combination of blue and yellow marbles is not known to you. Each possible combination from 0 blue marbles (and therefore 24 yellow ones) to 24 blue marbles (and therefore 0 yellow ones) is possible. At the end of the experiment you may take a look at the bag's contents.

Furthermore, there is a dice cup at the table containing a fair coin.

The timing of the experiment is as follows:

1. You choose one winning condition from the options on the Decision Sheet
2. One randomly selected participant blindly draws a marble from the bag.
3. The color of the drawn marble is announced.
4. Another randomly selected participant shakes the cup with the coin inside.
5. The result of the coin flip is announced.
6. You receive your payoff as it results from the payoff table below.

Your payoff will be determined based on the color of the marble drawn, the face of the coin, and the decisions you make. If the winning condition you have selected matches the color of the marble and face of the coin, you win the amount specified in the winning condition in addition to the guaranteed $10. If the winning condition does not match, you only receive the guaranteed $10. The winning conditions are explained in detail on the Decision Sheet.

# Decision sheet

Please indicate your choice by circling one of the Options below:

Win Conditions (Circle One)    Description

Option A If you choose Option A, you get \$21 if the ball drawn is blue and the coin shows "heads" or if the ball drawn is blue and the coin shows "tails". You get \$0 otherwise.

Option B If you choose Option B, you get \$21 if the ball drawn is yellow and the coin shows "heads" or if the ball drawn is yellow and the coin shows "tails". You get \$0 otherwise.

Option C If you choose Option C, you get \$20 if the ball drawn is blue and the coin shows "heads" or if the ball drawn is yellow and the coin shows "heads". You get \$0 otherwise.

Option D If you choose Option D, you get \$20 if the ball drawn is blue and the coin shows "tails" or if the ball drawn is yellow and the coin shows "tails". You get \$0 otherwise.

Option E If you choose Option E, you get \$22 if the ball drawn is blue and the coin shows "heads" or if the ball drawn is yellow and the coin shows "tails". You get \$0 otherwise.

Option F If you choose Option F, you get \$22 if the ball drawn is blue and the coin shows "tails" or if the ball drawn is yellow and the coin shows "heads". You get \$0 otherwise.

After you make your decision, please wait quietly for others to do the same. When everyone has reached a decision, an experimenter will come around to collect this decision sheet and hand out a questionnaire. After the questionnaire, the draw and flip will be made, and payments will be handed out.

## Questionnaire

(pg. 1) Please answer the following question:

What was your thought process when you made your decision?

(pg. 2) Please also answer the following questions:

Suppose there is an urn with 30 balls. There are 10 red balls in the urn. The other 20 balls are either white or black with an unknown composition.

One ball is randomly drawn from the urn. Which of the following alternatives would you prefer?

☐ You receive \$10 if a red ball is drawn.

☐ You receive \$10 if a white ball is drawn.

Suppose, instead, you were given the following alternatives. Which would you prefer?

☐ You receive $10 if a red ball or a black ball is drawn.

☐ You receive $10 if a white ball or a black ball is drawn.

(pg. 3) Please also answer the following questions:

What gender do you identify as?

☐ Woman

☐ Man

☐ Other (Feel free to elaborate in the space below, if you wish.)

What is your major, or intended major?

☐ Economics or Business Economics

☐ Other Business (including MIS, Marketing, etc.)

☐ Other (Please specify in the space below.)

How old are you?

(pg. 4) Please also answer the following questions:

Suppose there are two urns, each with 10 balls. In one urn (Urn A), there are 5 green and 5 orange balls. In the other urn (Urn B), the 10 balls are either green or orange with an unknown composition.

One ball is randomly drawn from an urn of your choice. You will win $10 if the ball is green. Which of the two urns would you prefer the ball be drawn from?

☐ Urn A.

☐ Urn B.

Suppose, instead, you will win $10 if the ball is orange. Which urn would you prefer?

☐ Urn A.

☐ Urn B.

(pg. 5) Please also answer the following questions:

Consider the real urn and coin that will be used to determine your payment.

How many blue balls do you think are in the urn?

How many yellow balls do you think are in the urn?

What do you think the chances are that the coin will come up heads?

Thank you for your responses! Please remain quiet while others finish the questionnaire. When everyone is done, the draw and flip will be performed. Then, an experimenter will come around to pay you.