Ambiguity Aversion in Game Theory: Experimental Evidence

Evan Calford*

August 6, 2015

PRELIMINARY – Comments welcome.

Abstract

This paper studies games with ambiguity averse agents, focusing on the relationship between preferences, beliefs over opponent’s preferences, and behaviour in normal form games. Using a carefully chosen $3 \times 2$ normal form game we find that a subject’s risk and ambiguity preferences affect the subject’s behaviour in normal form games in the direction suggested by economic theories. In contrast, we find no evidence that a subject’s beliefs over their opponent’s private preference information affect behaviour; although in a follow up treatment we find a strong effect of knowledge of an opponent’s preferences on behaviour. This paper is the first to present evidence of a link between ambiguity aversion in individual decision making and behaviour in strategic environments, and is also the first to consider empirically the role of beliefs over an opponent’s private information regarding the opponent’s ambiguity preferences. In addition, we find a positive correlation between subject’s risk and ambiguity preferences.

Keywords: Ambiguity Aversion, Game Theory, Experimental Economics, Preferences, Beliefs

JEL codes: C92, C72, D81

*Vancouver School of Economics, University of British Columbia, evancalford@gmail.com; I am particularly indebted to Yoram Halevy, who introduced me to the concept of ambiguity aversion and guided me throughout this project. Ryan Oprea provided terrific support and advice throughout. Special thanks to Mike Peters and Wei Li are also warranted for their advice and guidance. I also thank Li Hao, Kevin Song, Tom Wilkening and Simon Grant for helpful comments and discussion, as well as seminar audiences at the University of Melbourne, Australian National University and the University of Sydney. All mistakes are my own. Funding from SSHRC is gratefully acknowledged.
1 Introduction

In strategic interactions agents face uncertainty, in a Knightian sense\(^1\), regarding their opponent’s strategy choice. The standard approach to modeling the outcomes of strategic interactions – Nash equilibrium – assumes that all strategic uncertainty will be resolved in equilibrium. This assumption can, however, be difficult to justify. Consider the standard one-shot coordination game: without a strong focal point or correlation device there is no practical way for an agent to form a unique belief over their opponents’ choice of strategy. An implication of the Nash framework is that an agent who responds to ambiguity must, by definition, not be acting in equilibrium. Given the large body of evidence that human subjects respond to ambiguity in individual decision making environments, it seems prudent to study the effects of ambiguity in game theoretic contexts by moving beyond the Nash framework.

The study of the effects of ambiguity aversion on strategic interactions is an active area of theoretical research, but has received little empirical attention. The theoretical literature describes when and how ambiguity averse agents might deviate from Nash equilibrium behaviour, and the existing experimental literature typically identifies ambiguity preferences by assuming that deviations from Nash equilibrium are caused by non-neutral ambiguity preferences.\(^2\) This paper measures ambiguity preferences independently of behaviour in the “testing” games, allowing for a first time test of the fundamentals of ambiguity aversion in game theory. Is non-Nash behaviour more likely amongst subjects who are ambiguity averse? Can agents who respond to ambiguity in normal form games be identified by their responses to individual decision problems, such as Ellsberg urn tasks? Does private knowledge of ambiguity preferences play a role in determining behaviour? Are subject responses across games consistent with the subject holding a coherent mental model of their opponent’s preferences?

To answer these questions we use a laboratory experiment to measure ambiguity aversion, at the individual level, and study how behaviour in a carefully chosen normal form game is related

---

\(^1\) Knight (1921) identified a distinction between risk, where the likelihood of outcomes can be summarized as a quantitative probability, and uncertainty, where no such probabilities can be assigned. Modern authors tend to use the term ambiguity to refer to cases of uncertainty where the state space is well defined but objective probabilities are not available. In the context of games a mixed strategy represents probabilistic uncertainty (Knightian risk) over pure strategies, and ambiguity can be used to refer to (Knightian) uncertainty over mixed strategies. Furthermore, we shall use the term preference uncertainty to refer to the case where a player is not certain of their opponent’s preferences either in a probabilistic or non-probabilistic sense.

\(^2\) An overview of the experimental literature is included in appendix A.5, while the theoretical literature is considered in appendix B.
to our measure of ambiguity aversion. The testing game is designed so that the set of rationalizable strategies for ambiguity averse subjects (Epstein (1997)) is a superset of the set of Pearce (1984)/Bernheim (1984) rationalizable strategies, allowing for a partial separation of behaviour by type. The testing game also allows for a separation of the effects of ambiguity preferences from the effects of beliefs over an opponent’s ambiguity preferences and, in a follow-up treatment, a separation of strategic uncertainty (uncertainty regarding an opponent’s choice of strategy) from preference uncertainty (uncertainty regarding an opponent’s preferences). This separation allows, for the first time, an investigation of the role of ambiguity preference, beliefs over other’s ambiguity preferences and, in the follow-up treatment, knowledge of other’s ambiguity preferences on behaviour in a normal form game.

Consider the main testing game used in this experiment, as presented in figure 1. For a risk neutral\(^3\) row player with subjective expected utility (SEU) preferences, \(C\) is never a best response. Climbing the chain of rationalizability, once \(C\) is eliminated then \(Y\) is never a best response for the column player and once \(Y\) is eliminated \(B\) is never a best response for the row player. The unique rationalizable outcome of the game is \((A,X)\). Naturally, \((A,X)\) is also the unique Nash equilibrium of the game.

\[
\begin{array}{c|cc}
X & Y \\
\hline
A & 25,20 & 14,12 \\
B & 14,20 & 25,12 \\
C & 18,12 & 18,22 \\
\end{array}
\]

Figure 1: Main testing game

Now, consider an agent who is ambiguity averse, with the maxmin expected utility (MEU) preferences of Gilboa and Schmeidler (1989). For the row player, \(C\) is now a best response for at least some feasible beliefs. To see this, suppose that the row player faces complete uncertainty regarding their opponent’s strategy. Then, applying MEU preferences, they evaluate strategy \(A\) by considering the worst possible scenario (their opponent playing \(Y\)) and value the strategy such that \(U(A) = 14\). Similarly, when evaluating \(B\) they consider the worst possible scenario (their opponent playing \(X\)) so that \(U(B) = 14\) as well. However, \(U(C) = 18\) and therefore \(C\) is rationalizable for the row player. Obviously \(A\) and \(B\) are also rationalizable, and both column player strategies are also rationalizable. Therefore, under MEU preferences the rationalizable set is the full strategy set for both players.

\(^3\)We shall consider the effects of risk aversion in the main body of the paper, but for now consider the simplifying case of risk neutrality.
The argument in the previous paragraph hinges critically on the row player’s preferences. The rationalizable set is \((A, X)\) if and only if the row player can eliminate \(C\) in the first round. This allows for a separation of the role of preferences and beliefs, which is one of the key innovations of this paper. If the row player has SEU preferences then they should never play \(C\) independent of their beliefs regarding their opponent’s preferences. For the column player, they should never play \(Y\) if they believe that their opponent has SEU preferences independent of their own preferences.

The separation of the role of preferences and beliefs is a novel design feature that allows for an investigation of the structural underpinnings of ambiguity averse solution concepts. The results are mixed. Preferences play an important role, as they should. On the other hand, beliefs (which are measured independently of behaviour in the testing games) do not play their expected role: behaviour in the testing game is independent of a subject’s beliefs regarding their opponent’s preferences. A follow-up treatment, where subjects were shown their opponent’s preferences before playing the testing game, finds that the subjects have a very low degree of confidence in their beliefs regarding their opponent’s preferences. When a subject knows their opponent’s preferences then behaviour conforms to theoretical predictions rather well. The data collected regarding subject preferences also contributes to the decision theory literature on ambiguity preferences and their relationship to risk preferences; we find that risk preferences are positively correlated with ambiguity preferences.\(^4\)

The experiment is also designed to mitigate a number of factors that have been identified as affecting the elicitation of ambiguity preferences. Recent research has identified that subject confusion can significantly lower measured ambiguity aversion (Chew et al. (2013)), that experiments with ambiguity can be particularly susceptible to violations of incentive compatibility across tasks (Baillon et al. (2014), Azrieli et al. (2014)) and that framing effects may be particularly strong (Chew et al. (2013)). The experimental design presented here mitigates these factors by using extensive, incentivized, comprehension tasks to test for subject understanding, realizing objective randomizations prior to realizing subjective randomizations, and presenting all tasks in a unified normal-form game framing.

The interpretation of the results presented in this paper is not tied to any particular model of ambiguity aversion. The experimental design in this paper is intended to shed light on the general phenomena of ambiguity aversion in game theory, rather than choose between competing models. Understanding the role of ambiguity aversion in strategic contexts may be of use for a range of applications including models of coalition formation and voting choice, bargaining models,

\(^4\)See footnote 14 for references on this topic.
no trade theorems, search and matching models, and empirical models with latent choice over strategic variables.

This paper proceeds as follows. Section 2 provides a brief overview of some relevant theoretical considerations, while section 3 presents the experimental design in detail. Section 4 presents the experimental results, and section 5 presents an additional treatment motivated from these results. Section 6 provides a discussion and conclusion. The appendices are organized so that additional information relevant for the experimental design are collected in appendix A, appendix B provides additional theoretical details and proofs, and appendix C presents additional results not included in the main text.

2 Theoretical considerations

The identification of the relationship between preferences and “reasonable” strategies in the main testing game can be motivated either using rationalizability arguments or equilibrium concepts (i.e. Nash equilibrium for SEU subjects and an appropriately chosen ambiguity averse equilibrium concept for ambiguity averse subjects). We use rationalizability rather than equilibrium concepts in the body of the paper because of the stronger epistemic assumptions required to justify the use of equilibrium; however, we provide two equilibrium derivations (using equilibria from Lo (2009) and Dow and Werlang (1994)) in appendix B.3 for the interested reader.

Throughout we assume that subjects choose from their set of pure strategies, and do not play mixed strategies. This is consistent with the experimental implementation where subjects where required to select a pure strategy choice for each game. The reason for this choice, which is common amongst the ambiguity aversion in game theory literature, is that models of ambiguity aversion typically imply a strict preference for mixed strategies or are not able to define a utility level for mixed strategies at all. Appendix B, as well as Eichberger and Kelsey (2000) and Calford (2015), contain extensive discussion on the role of mixed strategies in games with ambiguity averse agents.

The rest of this section formalizes the intuition provided in the introduction and extends the analysis to allow for preferences to be private information.
2.1 Rationalizability

In this section we formalize the interactions between preferences and rationalizability in the game in figure 1. For agents with SEU preferences we use the standard notion of rationalizability (Pearce (1984) and Bernheim (1984)), while for non SEU agents we use the closely related notion of rationalizability developed in Epstein (1997).

The Epstein (1997) notion of rationalizability is the natural extension of the Pearce-Bernheim notion to agents with non-standard preferences. In each round we eliminate all strategies that are never a best response to any potential beliefs that the agent might hold. The difference is that now the beliefs may be more general than standard (i.e. set valued or a distribution instead of point valued), and the preferences may also be more general than standard. In the Epstein framework we can think of rationalizability with respect to a preference structure. The only conceptual difference between the Pearce-Bernheim framework and the Epstein framework is the treatment of mixed strategies: Epstein (1997) restricts the feasible set of strategies to consist only of pure strategies, although agents may still hold beliefs over the mixed strategies of their opponents (following a population or belief-based interpretation of mixed strategies).

We shall develop and state some propositions regarding the game presented in figure 1. For simplicity, we shall develop a minimal working example that illustrates the different roles of strategic uncertainty and private preference information in our simple game. A more general analysis could, for example, be developed using a framework similar to that presented in Grant et al. (2013).

Consider two different preference structures for the row player. First, we define MEU preferences (Gilboa and Schmeidler (1989)) where an agent’s beliefs regarding their opponents strategies is a closed and convex subset of probability measures over their opponent’s strategy set. For our game, the set of feasible row player beliefs is given by $\Phi_R \subseteq \Delta(\{X,Y\})$. Given $\Phi_R$ an agents preferences are represented by

$$\min_{\phi_R \in \Phi_R} \sum_{a_C \in \{X,Y\}} u_R(a_R, a_C)\phi_R(a_C).$$

Second, we note that SEU preferences are the restriction of equation 1 to the case where $\Phi_R$ is a singleton. We now deal with the case where all preference information is common knowledge.

**Proposition 1.** Suppose that preferences are common knowledge. Then, for the game in figure 1, the set of rationalizable outcomes is:

1. $\{(A,X)\}$ if the row player has SEU preferences,
2. all possible outcomes if the row player has MEU preferences.

Notice that proposition 1 does not restrict the column player’s preferences at all because the column player’s preferences play no role in determining the size of the rationalizable set. Also note that the use of MEU preferences to model ambiguity aversion is not essential: any preference structure that allows for a risk neutral agent to hold the preferences \((18, 1) \succ (25, E; 14, E^c)\) and \((18, 1) \succ (25, E^c; 14, E)\) concurrently will be admissible (where \((18, 1)\) is the receipt of $18 for sure and \((25, E; 14, E^c)\) is a prospect that pays $25 when some event, \(E\), occurs and $14 when the event does not occur). In a recent working paper Battigalli et al. (2015) independently establish an equivalent result, illustrated using an example on a normalised version of the game studied here, for the case of Klibanoff et al.’s (2005) smooth ambiguity aversion preferences. Their example also highlights and reaffirms that “the risk and ambiguity attitudes of the (column player) are immaterial.”

The assumption that preferences are common knowledge is obviously unrealistic, and can easily be relaxed. We now consider the case where the row player has private information regarding their preferences, modeling the game as a Bayesian game. Suppose that the column player has a prior belief \(\alpha \in [0, 1]\) that the row player has MEU preferences, and with complementary probability believes that the row player has SEU preferences.

**Proposition 2.** Suppose that the column player believes that the row player has MEU preferences with probability \(\alpha \in [0, 1]\). The value of \(\alpha\) is common knowledge. Then, for the game in figure 1, the set of rationalizable outcomes is:

1. \(\{(A, X)\}\) if the row player has SEU or MEU preferences and \(\alpha < \frac{4}{9}\),
2. \(\{(A, X), (A, Y), (B, X), (B, Y)\}\) if the row player has SEU preferences and \(\alpha \geq \frac{4}{9}\),
3. all possible outcomes if the row player has MEU preferences and \(\alpha \geq \frac{4}{9}\).

One key implication of proposition 2 is that \(Y\) is rationalizable if and only if \(\alpha \geq \frac{4}{9}\). In some sense, the standard Bayesian game assumption that prior beliefs are common knowledge is still too restrictive because the row player’s second order belief over the column player’s first order belief over the row player’s preferences may also be important. This could be relaxed ala Grant et al.

---

5It is possible to relax the knowledge requirements even further by modeling the game as a Savage game ala Grant et al. (2013), but for the current game the Bayesian formulation generates the same intuition in a more familiar environment.
(2013) at a significant complexity cost, although we do not attempt this here. Nevertheless, the intuition is clear: the row player’s preferences and the column player’s first order beliefs are the primary determinants of the rationalizable set.

In all of the above propositions and discussions, the analysis goes through unchanged if we replace “SEU preferences” with “risk neutral preferences” and “MEU preferences” with “strongly risk averse preferences”. Alternatively, we could replace “SEU preferences” with “risk neutral SEU preferences” and “MEU preferences” with “MEU preferences or strongly risk averse SEU preferences”. Roughly speaking, the role of risk aversion in the testing game mirrors the role of ambiguity aversion. The exact procedure used to control for risk preferences is discussed in sections 3.1 and 3.2.

3 Experimental Design

Each subject played 7 two-player normal form games. There are only 4 distinct games, with subjects playing 3 of the games as both the row player and the column player. The first two games were used to measure the subjects’ risk and ambiguity preference (as row players) and their beliefs regarding their opponent’s risk and ambiguity preference (as column players); these games are referred to as the classification games.

The remaining two games were then used to test whether the subjects preferences and beliefs, coupled with an appropriate solution concept, can predict their behaviour in normal form games; these games are referred to as the testing games. The testing games were constructed so that behaviour as the row player in the first testing game is predicted to depend only on the subject’s preferences (and not their beliefs regarding their opponent’s preferences), behaviour as the column player in the first testing game is predicted to depend only on the subject’s beliefs regarding their opponent’s preferences (and not their own preferences), and behaviour in the second testing game (which is only played once, as it pseudo-symmetric) is predicted to depend on both the subject’s preferences and their beliefs regarding their opponent’s preferences. Only the first testing game is presented in the main text, the second is relegated to appendix C.1.6

6Given the results that were observed in the first testing game, interpretation of the results from the second testing game is difficult.
### 3.1 Classification games

The first (ambiguity) classification game is shown in figure 2. The game involves two ball draws, one from the U urn (figure 3) and one from the K urn (figure 4). Therefore there are four possible states of nature, but only two payoff tables. The left payoff table represents the state red ball drawn from the U urn and yellow ball drawn from the K urn: \((R_U, Y_K)\). The right payoff table represents the state \((Y_U, R_K)\). The payoffs for state \((R_U, R_K)\) are found by adding the two payoff tables together, and the payoffs in state \((Y_U, Y_K)\) are identically 0 for both players. The relationship between states and payoffs was carefully explained to the subjects, and the subjects needed to understand this relationship in order to correctly fill in the related drop down menus correctly. The drop down menus are discussed in more detail in section A.2.

<table>
<thead>
<tr>
<th></th>
<th>(S')</th>
<th>(M')</th>
</tr>
</thead>
<tbody>
<tr>
<td>(S)</td>
<td>30.1, 15</td>
<td>30.1, 0</td>
</tr>
<tr>
<td>(M)</td>
<td>0, 0</td>
<td>0, 15</td>
</tr>
</tbody>
</table>

Red ball drawn from U urn

<table>
<thead>
<tr>
<th></th>
<th>(S')</th>
<th>(M')</th>
</tr>
</thead>
<tbody>
<tr>
<td>(S)</td>
<td>0, 15</td>
<td>0, 0</td>
</tr>
<tr>
<td>(M)</td>
<td>30, 0</td>
<td>30, 15</td>
</tr>
</tbody>
</table>

Red ball drawn from K urn

**Figure 2:** Classification game 1. This game is used to measure the row player’s ambiguity aversion and the column player’s belief of the row player’s ambiguity aversion.

**Figure 3:** U urn. The U urn consists of 10 balls, each of which may be either red or yellow. The total number of red balls in the urn lies between 0 and 10.

**Figure 4:** K urn. The K urn contains 5 red and 5 yellow balls.

Given that row player payoffs are independent of the column player strategy choice, we can view the row player as facing a choice between a bet that pays $30.10 if a red ball is drawn from the U urn and a bet that pays $30 if a red ball is drawn from the K urn. Given that red and yellow are interchangeable labels, subjects are assumed to hold symmetric beliefs about the distribution of balls in the U urn. If a subject has SEU preferences, then they should strictly prefer strategy \(S\) (the bet on the U urn). A subject with ambiguity averse preferences should prefer strategy \(M\) (the
bet on the K urn).\textsuperscript{7}

**Conclusion 1.** A choice of $S$ by the row player in the game in figure 2 is evidence of ambiguity neutrality, and a choice of $M$ is evidence of ambiguity aversion.

Now, consider the column player in the game in figure 2. The column player is tasked with predicting the row player’s action. If the outcome of the game is $(S, M')$ or $(M, S')$ then the column player receives $0$ in all states. So the rational column player will play $S'$ if they believe that the row player is more likely to choose $S$, and will play $M'$ if they believe that the row player is more likely to choose $M$.

**Conclusion 2.** A choice of $S'$ by the column player in the game in figure 2 is evidence that they believe that their opponent is ambiguity neutral, and a choice of $M'$ is evidence that they believe their opponent is ambiguity averse.

\[
\begin{array}{c|ccc}
 & L' & I' & H' \\
\hline
L & 25,30 & 25,0 & 25,0 \\
I & 11,0 & 11,30 & 11,0 \\
H & 15,0 & 15,0 & 15,30 \\
\end{array} \quad \begin{array}{c|ccc}
 & L' & I' & H' \\
\hline
L & 10,30 & 10,0 & 10,0 \\
I & 23,0 & 23,30 & 23,0 \\
H & 15,0 & 15,0 & 15,30 \\
\end{array}
\]

Red ball drawn from K urn \quad Yellow ball drawn from K urn

Figure 5: Classification game 2. This game is used to measure the row player’s risk aversion and the column player’s belief of the row player’s risk aversion.

The second classification game is shown in figure 5, and it has a very similar structure to the first classification game. The row player chooses which risky prospect they would like to hold, and the column player attempts to predict the row player’s preferences. A highly risk averse row player will choose $H$, while a risk neutral (or low risk aversion) row player will choose $L$. Subjects with intermediate levels of risk aversion will choose $I$. Similarly, a subject that chooses $L'$ believes their opponent to have low risk aversion, while a subject that chooses $H'$ believes their opponent to be rather risk averse.

In the next section we discuss the role of risk aversion in our main testing game. To form a link between the classification game in figure 5 and the main testing game requires some assumptions

\textsuperscript{7}It is possible that an ambiguity averse agent may still prefer strategy $S$ if their ambiguity aversion is very slight. However, it seems unlikely that many subjects, if any, would fall into this category given that the premium for betting on the ambiguous urn is only 10 cents.
about the utility function. We proceed by considering two common utility functions: constant relative risk aversion (CRRA, equation 2) and constant absolute risk aversion (CARA, equation 3).8

\[ u(c) = \frac{c^{1-\beta} - 1}{1 - \beta} \] (2)

\[ u(c) = 1 - e^{-\rho c} \] (3)

The following table presents the risk aversion implications of various choices in the risk classification game. Note that the importance of the risk aversion measure lies in whether the subject has risk aversion strong enough to alter the rationalizable sets in the testing game; the parameterization of the utility function is unimportant. One potential method to ensure that the mapping from the classification game to the rationalizable sets of the testing game is “clean” is to use exactly the same payoffs across games. This method was not used, however, to avoid any potential anchoring effects across games.

<table>
<thead>
<tr>
<th>Choice in Risk game</th>
<th>Utility parameterization</th>
<th>CRRA</th>
<th>CARA</th>
</tr>
</thead>
<tbody>
<tr>
<td>L</td>
<td>( \beta &lt; 0.84 )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>I</td>
<td>( 0.84 &lt; \beta &lt; 1.88 )</td>
<td>( \rho &lt; 0.05 )</td>
<td>( 0.05 &lt; \rho &lt; 0.12 )</td>
</tr>
<tr>
<td>H</td>
<td>( 1.88 &lt; \beta )</td>
<td>( 0.12 &lt; \rho )</td>
<td></td>
</tr>
</tbody>
</table>

Table 1: Utility parameters implied by choices in the game in figure 5. All figures are rounded to 2 decimal places, and are therefore approximate.

### 3.2 Testing games

The first testing game, reproduced in figure 6, is the same game that was introduced in the introduction. In the introduction we took the normal game theoretic approach of assuming that payoffs were von-Neumann Morgenstern utility values. Once we allow for the fact that all payoffs are in

---

8Note the implicit assumption that subjects treat the experiment as an independent event, and do not integrate their outside wealth into their utility functions. This is standard throughout experimental economics. A theoretically more correct formulation would use \( u(c+w) \) where \( w \) is the subjects initial wealth level, but we follow the experimental standard here. As suggested by Simon Grant, readers who are troubled by this formulation should focus on the CARA utility parameterization (and not the CRRA parameterization).
dollar amounts, the analysis in the introduction (and section 2.1) will hold whenever the subject’s Bernoulli utility function satisfies:

\[ u(18) < \frac{1}{2} (u(25) + u(14)). \]  

(4)

When equation 4 is violated all strategies are rationalizable even for SEU subjects. Equation 4 holds under CRRA utility when \( \beta < 1.93 \), and holds under CARA utility when \( \rho < 0.10 \).

We therefore conclude that a subject who chooses \( L \) in the risk measurement game satisfies equation 4 and that, for such a subject, propositions 1 and 2 hold as stated. Furthermore, a subject who chooses \( H \) in the risk measurement game will likely violate equation 4, implying that all strategies are rationalizable for such an agent. Things are less clear for subjects that choose \( I \) in the risk measurement game. We take the approach of pooling these subjects with the subjects that choose \( L \). Alternatively, we could have chosen to remove these subjects from the sample. We use the former approach, noting that only 10% of subjects choose \( I \) in the game in figure 5 and that removing them has no effect on the results.

We summarize our predicted behaviour across games as follows.

**Conclusion 3.** Subjects whose preferences satisfy low risk aversion (choose \( L \) or \( I \) in the game in figure 5) and ambiguity neutrality (choose \( S \) in the game in figure 2) are predicted to play \( A \) in the game in figure 6.

**Conclusion 4.** Subjects whose preferences satisfy high risk aversion (choose \( H \) in the game in figure 5) or ambiguity aversion (choose \( M \) in the game in figure 2) are predicted to play any of \( \{A, B, C\} \) in the game in figure 6.

We can repeat the above analysis for column players. Note that a choice of \( M' \) in the game in figure 2 is consistent with \( \alpha < \frac{1}{2} \), while the cutoff value of \( \alpha \) in proposition 2 is \( \frac{4}{5} \). There is, therefore, the possibility that subjects who choose \( M' \), but are very uncertain about their opponents

\[
\begin{array}{|c|c|c|}
\hline
& X & Y \\
A & 25,20 & 14,12 \\
B & 14,20 & 25,12 \\
C & 18,12 & 18,22 \\
\hline
\end{array}
\]

Figure 6: Testing game 1. The row player’s rationalizable strategy set varies with their preferences. The column player’s rationalizable strategy set varies with their belief of the row player’s preferences.
preferences \((\frac{4}{9} < \alpha < \frac{1}{2})\) may be misclassified. We ignore this possibility for now, but consider a work around in section 5, and conclude:

**Conclusion 5.** Subjects who believe their opponent’s preferences satisfy low risk aversion (choose \(L'\) or \(I'\) in the game in figure 5) and ambiguity neutrality (choose \(S'\) in the game in figure 2) are predicted to play \(X\) in the game in figure 6.

**Conclusion 6.** Subjects who believe their opponent’s preferences satisfy high risk aversion (choose \(H'\) in the game in figure 5) or ambiguity aversion (choose \(M'\) in the game in figure 2) are predicted to play either \(\{X,Y\}\) in the game in figure 6.

The second testing game, which is a variant of the prisoner’s dilemma, is discussed in Appendix C.1. It was designed to test the effects of ambiguity preferences and beliefs over an opponent’s preferences jointly, rather than separately as in the main testing game.

### 3.3 Experimental conditions

All sessions were held in the ELVSE lab at the Vancouver School of Economics. There were 10 sessions held in March and April 2014, and a further 10 sessions held in September 2014\(^9\), with between 8 and 12 subjects per session. There were some minor changes to the instructions made between the April and September sessions, otherwise all sessions were identical. The September instructions are included in the appendix. Sessions lasted between 60 and 90 minutes, and the average payment was $26.60. Subjects were recruited from the ELVSE implementation of the ORSEE subject pool (Greiner (2004)), which is overwhelmingly made up of UBC undergraduate students. The experiments were run using the Redwood experimental software tool (Pettit et al. (2014)).

A range of other important, yet technical, experimental considerations are discussed in detail in the experimental methodology appendix A.

### 4 Results

This section presents the experimental results. Section 4.1 presents the results relating to individual preferences and section 4.2 presents the results of the testing game.

\(^9\)There were not enough subjects available to efficiently run sessions during the summer semester.
4.1 Preferences

We begin our tour of the results with a look at the preferences of our subjects.

<table>
<thead>
<tr>
<th>Risk aversion</th>
<th>Ambiguity preference</th>
<th>Neutral</th>
<th>Averse</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>69 (73%)</td>
<td>25 (27%)</td>
<td>94</td>
</tr>
<tr>
<td>Int.</td>
<td>5 (42%)</td>
<td>7 (58%)</td>
<td>12</td>
</tr>
<tr>
<td>High</td>
<td>23 (46%)</td>
<td>27 (54%)</td>
<td>50</td>
</tr>
<tr>
<td></td>
<td>97 (62%)</td>
<td>59 (38%)</td>
<td>156</td>
</tr>
</tbody>
</table>

Table 2: Subject’s own risk preferences crossed with own ambiguity preferences, restricted to subjects who passed the comprehension test for the relevant games. Percentages are the cell count as a percentage of the row total. Non-directional Fisher’s exact test \( p = 0.002 \).

Table 2 presents the data on risk and ambiguity aversion. The sample is restricted to subjects who filled in the comprehension drop down menus correctly on the first attempt for the games that were used to measure risk and ambiguity aversion; 50 of the 206 subjects failed this test. Of the 156 remaining subjects, 59 (38%) were classified as ambiguity averse. This figure is at the lower end of the level of ambiguity aversion reported in previous papers, and lower than that measured previously in 2-urn Ellsberg tasks. We find that only a quarter of subjects with low risk aversion are ambiguity averse, while more than half of subjects with medium or high risk aversion are also ambiguity averse. A non-directional Fisher exact test rejects the null hypothesis of independence of risk and ambiguity preference at the 1% level \( p = 0.002 \). Furthermore, based on subject reported area of study, STEM (plus economics) students were significantly more likely to be ambiguity averse than other students.

10Clearly there are many different inclusion criteria that could be constructed from the comprehension data. The criterion that was chosen was determined ex-ante. See appendix C.3 for a discussion of the comprehension data, inclusion criterion and robustness.

11Chew et al. (2013) provide an overview of previous Ellsberg urn experimental results. For the 2-urn case, as used in this paper, previous studies have found that between 47% and 78% of subjects are ambiguity averse (with a weighted mean of 66%). For the 1-urn (3-colour) Ellsberg task, previous studies have found that between 79% and 8% of subjects are ambiguity averse (with a weighted mean of 27%). Pilot sessions suggest that the framing of the decision problem in a bi-matrix format may cause lower levels of ambiguity aversion to be measured.

12The choice of statistical tests for categorical data is an oft-debated topic. The Fisher exact test is the de-facto standard in experimental decision theory, and is also more conservative than some other alternatives (such as the Barnard exact test). An additional appendix on the statistical methodology used in this paper is available from the author, on request.

13For STEM students 31 of 61 subjects exhibited ambiguity aversion, while for other students only 20 of 73
**Result 1.** *Risk and ambiguity preferences are positively correlated.*

The previous literature on the correlation between risk and ambiguity preferences has produced very mixed results. Some studies have found positive correlation, others have found no correlation, and others have found correlations under some circumstances but not others.\(^{14}\) The evidence provided here is of a very base variety - once the framing of the games is stripped away, subjects were faced with discrete choice sets. Given that decisions over discrete choice sets form the building blocks of decision theory under uncertainty, there is a strong case to be made that decisions over discrete choice sets are the correct domain for examining preferences.

The data also presents a strong relationship between a subject’s preferences and their beliefs regarding their opponent’s preferences. Further investigation of this relationship is relegated to appendix C.2, however, as there is strong evidence (discussed in section 5) that subjects had a very low level of confidence in their predictions of their opponent’s behaviour. In this context of uncertainty, projecting their own preferences onto their opponent provides a sensible focal point that was followed by most subjects.

**4.2 Testing games**

We now turn our attention to the testing games, beginning with row player behavior in the game in figure 6. Table 3 presents, on the columns, each subject’s strategy choice in the game in figure 6 and, on the rows, the rationalizable set of strategies based on their preferences. Ambiguity neutral and low risk aversion subjects are expected to play the unique Bernheim/Pearce rationalizable strategy of $A$, while for other subjects all strategies are rationalizable.

Table 3 restricts the sample to the 125 subjects who passed the comprehension tests as the row player for the games in figures 2, 5 and 6. The sample is almost evenly split between subjects who are expected to play $A$, referred to as subjects ‘Unique’ type subjects, and subjects for which all strategies are rationalizable, referred to as ‘Full’ type subjects. Note that even for Full subjects a choice of $A$ is rationalizable, a consequence of our partial set identification of types. In the game in subjects were ambiguity averse ($p = 0.007$). Area of study information is not available for 23 subjects who passed the comprehension test, because of either computer crashes or subjects not reporting. There are also some differences in behaviour in the testing games between STEM and non-STEM students, but these are not surprising given the differences in preferences.

\(^{14}\)A non-exhaustive list of papers that have found a positive correlation between risk and ambiguity aversion includes: Abdellaoui et al. (2011), Bossaerts et al. (2009) and Dean and Ortoleva (2014) . A similar list on the other side of the debate includes: Curley et al. (1986) and Di Mauro and Maffioletti (2004).
Row player action | A          | B          | C          |
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Rationalizability prediction</td>
<td>{A}</td>
<td>44 (72%)</td>
<td>3 (5%)</td>
</tr>
<tr>
<td></td>
<td>{A, B, C}</td>
<td>34 (53%)</td>
<td>8 (13%)</td>
</tr>
</tbody>
</table>

Table 3: Subject’s rationalizable set crossed with their strategy choice in the game in figure 6, restricted to subjects who passed the comprehension test for the relevant games. A subject has a rationalizable set of {A} if they have low or intermediate risk aversion and are ambiguity neutral; otherwise they have a rationalizable set of {A, B, C}. Predicted responses are bold and underlined. Percentages are the cell count as a percentage of the row total. Directional Fisher’s exact test \( p = 0.024 \).

figure 6 72% of Unique types play A, while only 53% of Full types play A. Full types are also more likely to play both B and C. We wish to test whether this difference in behaviour is statistically significant; the appropriate statistical test is a directional Fisher exact test.\(^{15}\)

The null hypothesis is that the of subjects playing each strategy is independent of the rationalizability prediction. The alternative hypothesis is that \( p_A^{\{A\}} \geq p_A^{\{A,B,C\}} \), \( p_B^{\{A\}} \leq p_B^{\{A,B,C\}} \) and \( p_C^{\{A\}} \leq p_C^{\{A,B,C\}} \), where \( p_A^{\{A\}} \) represents the proportion of subjects that were predicted to play {A} that actually played A. The null hypotheses is rejected at the 5% level (\( p = 0.024 \)).

**Result 2.** Behaviour as the row player in the game in figure 6 is correlated with a joint measure of ambiguity and risk preferences.

Of particular note are the 17 subjects who were uniquely predicted to play A but actually played B or C instead. As discussed in Kelsey and le Roux (2015a), one potential explanation for these subjects is that they do not view an Ellsberg urn as a source of ambiguity but do view their opponent’s strategy choice as a source of ambiguity.\(^{16}\) An alternative, related, explanation is

\(^{15}\)An additional appendix outlining the procedure used to implement a directional Fisher exact test in tables larger than \( 2 \times 2 \) is available from the author on request.

\(^{16}\)On most dimensions there were no gender differences found in this experiment, although there is some evidence (albeit somewhat speculative) that women perceived their opponent’s strategy to be relatively more ambiguous than the Ellsberg urn.

There was no gender difference found with respect to ambiguity preference, but women were more risk averse than men (\( p = 0.035 \)). Consequently, women played more conservatively in the testing game (choosing C more often than men, and choosing A and B less often; \( p = 0.043 \)). Given previous research (Borghans et al. (2009)) which has documented higher levels of risk aversion amongst female experimental subjects, this is reasonably unsurprising. However, when restricting the sample to risk neutral and ambiguity neutral subjects women were still significantly more conservative in their behaviour in the testing game (\( p = 0.032 \)). There is evidence that the gender composition
that some subjects focus on the symmetric nature of the Ellsberg urn task and therefore consider it equivalent to a 50-50 bet. The testing game is not, however, symmetric and does not provide a natural anchoring point for a subject’s expectations. Measuring ambiguity preferences using alternative sources of ambiguity, rather than Ellsberg urns, would provide a potential test of these explanations.

<table>
<thead>
<tr>
<th>Risk Aversion</th>
<th>Ambiguity Neutral</th>
<th>Ambiguity Averse</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>A: 72%</td>
<td>A: 58%</td>
<td>p = 0.045</td>
</tr>
<tr>
<td></td>
<td>B: 5%</td>
<td>B: 21%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>C: 22%</td>
<td>C: 21%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>N= 61</td>
<td>N= 24</td>
<td></td>
</tr>
<tr>
<td>High</td>
<td>A: 61%</td>
<td>A: 41%</td>
<td>p = 0.22</td>
</tr>
<tr>
<td></td>
<td>B: 6%</td>
<td>B: 9%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>C: 33%</td>
<td>C: 50%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>N= 18</td>
<td>N= 22</td>
<td></td>
</tr>
<tr>
<td>Any</td>
<td>A: 70%</td>
<td>A: 50%</td>
<td>p = 0.017</td>
</tr>
<tr>
<td></td>
<td>B: 5%</td>
<td>B: 15%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>C: 25%</td>
<td>C: 35%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>N= 79</td>
<td>N= 46</td>
<td></td>
</tr>
</tbody>
</table>

Table 4: Subject’s strategy choice as the row player in the game in figure 6 as a function of the subject’s risk and ambiguity preferences, restricted to subjects who passed the comprehension test for the relevant games. The p-values are calculated via a directional Fisher’s exact test with null hypothesis that the distribution of behaviour is identical for ambiguity neutral and ambiguity averse subjects.

Table 4 provides a more complete view of the row player data which allows us to focus on the effects of ambiguity aversion; again, the sample is restricted to the subjects who passed the relevant comprehension tasks. The bottom row of the table presents the effect of ambiguity aversion on behaviour, aggregated across subjects of any risk preference. This unconditional measure is useful for comparing to the results from Kelsey and le Roux (2015a) which does not contain data on risk preferences. Ambiguity neutral subjects are, on average, 20 percentage points more likely to play the unique Pearce/Bernheim rationalizable strategy, A, in the testing game and 10 percentage of sessions influences women’s behaviour in games (Vesterlund et al. (2013), for example), and given that we did not control the gender composition of sessions ex-ante nor is the data set large enough to statistically control for this ex-post, we recommend caution in interpreting this result. Nonetheless, it may warrant further investigation in future experiments.
points less likely to choose both $B$ and $C$ than ambiguity averse subjects; the null hypothesis of independence is rejected at the 5% level by a directional Fisher exact test ($p = 0.017$).

The top row of table 4 excludes high risk aversion subjects. It can, therefore, be used to examine the effect of ambiguity aversion, providing a measure that is unconfounded by risk aversion: for these subjects, the size of the rationalizable set of strategies varies only with their ambiguity preferences. The sample size drops substantially and the sample is skewed towards ambiguity neutral subjects (which is not surprising given the high correlation between risk and ambiguity aversion). Ambiguity averse subjects are less likely to play $A$ and are more likely to play $B$ while the proportion of subjects playing $C$ is almost identical across ambiguity averse and ambiguity neutral subjects. Again, we use a direction Fisher exact test to test the null hypothesis of independence against the alternative hypothesis ambiguity averse subjects are more likely to play $B$ and $C$ (and less likely to play $A$) than ambiguity neutral subjects. The null hypotheses is rejected at the 5% level ($p = 0.045$).

Result 3. Behaviour as the row player in the game in figure 6 is correlated with ambiguity preferences.

Result 4. For subjects with low risk aversion, behaviour as the row player in the game in figure 6 is correlated with ambiguity preferences.

As is clear from the top row of table 4, result 4 is identified from the fact that ambiguity averse subjects play $A$ less than, and $B$ more than, ambiguity neutral subjects. Intuition might suggest that an ambiguity averse subject should, instead, play $C$ because it is the safe strategy. It is important to note, however, that the rationalizable set includes $B$ for such subjects. In Lo’s (2009) Lo-Nash equilibrium there does not exist an equilibrium where an ambiguity averse row-player plays $C$ with probability 1: any equilibrium that is not the pure strategy $(A, X)$ must necessarily be a mixed equilibrium. The reasoning is that pure $\{C, Y\}$ is not stable – if the row player is aware of the support of the column player’s strategy (a condition that is much weaker than the usual Nash implication that each player is aware of their opponent’s exact strategy) then the row player would deviate. An intuitive level-$k$ style explanation for an ambiguity averse subject is that they are performing two rounds of reasoning: “It is obvious that $C$ is the safe option, and I

\[17\] Relevant equilibrium concepts for ambiguity averse subjects include fully mixed equilibria as well. Interestingly, this provides a point of separation between the effects of risk and ambiguity aversion in the testing game. For subjects with high risk aversion there only exists equilibria where the row player mixes between 2 of their 3 strategies – there does not exist fully mixed equilibria. This observation is consistent with results presented in table 4.

\[18\] See appendix B.3 for a formal proof of this result using the equilibrium in Lo (2009).
expect that my opponent will think that I would like to play C because it is safe. But, given that this is the case, then surely I should choose B!"

In the middle row of table 4 there is no theoretical reason to expect ambiguity aversion to affect behaviour because all strategies are rationalizable for subjects with high risk aversion (irrespective of their ambiguity aversion). Nevertheless, there is an effect of ambiguity aversion on behaviour that is approximately the same magnitude as for low risk aversion subjects. This effect is not, however, statistically significant because of the smaller sample size of high risk aversion subjects.

We now turn to analyzing the relationship between beliefs over opponent’s preferences and behaviour as the column player in the game in figure 6. Table 5 restricts the sample to the 113 subjects who passed the comprehension tests as the column player for the games in figures 2, 5 and 6. Most of the subjects who failed the comprehension failed it for the game in figure 2. The game in figure 2 measured a subject’s beliefs regarding their opponents ambiguity preference. In order to pass the comprehension for this game a subject had to correctly identify that their opponent’s payoffs depended only on the ball draws (and not the subject’s behaviour), correctly describe the payoffs associated with each of their opponent’s strategies and identify how their own payoffs varied with their opponent’s strategy choice.19

<table>
<thead>
<tr>
<th>Rationalizability Prediction</th>
<th>Column Player Action</th>
</tr>
</thead>
<tbody>
<tr>
<td>{X}</td>
<td>X</td>
</tr>
<tr>
<td>{Y}</td>
<td>Y</td>
</tr>
</tbody>
</table>

Table 5: Subject’s set of rationalizable strategies crossed with their column-player strategy choice, restricted to subjects who passed the comprehension test for the relevant games. A subject has a rationalizable set of {X} if they believe that their opponent has low or medium risk aversion and believe that their opponent is ambiguity neutral; otherwise their rationalizable set is {X,Y}. Rationalizable predictions are bold and underlined. Percentages are the cell count as a percentage of the row total. Directional Fisher’s exact test \( p = 0.358 \).

The sample is evenly split between subjects who believe that their opponents are Unique types, and subjects who believe their opponents are risk or ambiguity averse. Subjects who believe their opponents to be Unique types should recognize that strategy C is never a best response for their opponent, and therefore play X. Subjects who believe their opponents are risk or ambiguity averse may assign a positive weight to their opponent playing C, and therefore may play either X or Y.

19 A full analysis of the comprehension data is available in the appendix.
As can be seen in table 5 the proportion of subjects that played X is almost identical across the two classifications of subjects. This is confirmed by the directional Fisher exact test of a null hypothesis of independence against the alternative hypothesis that the classification is correlated with strategy choice. The null hypothesis that behaviour as the column player in the game in figure 6 is independent of beliefs over the opponent’s preferences cannot be rejected at standard significance levels ($p = 0.358$).

We have established that a joint measure of beliefs over an opponent’s risk and ambiguity preferences cannot explain behaviour as the column player in the game in figure 6. Unsurprisingly, beliefs over ambiguity preferences alone do not explain behaviour in the normal form game either, whether we look at ambiguity preferences independently of risk preferences or not. The complete data set for column player responses, restricted to subjects that passed the relevant comprehension tasks, is shown in table 6.20

**Result 5.** *Neither beliefs over risk preferences nor beliefs over ambiguity preferences explain behaviour for the column player in the game in figure 6.*

<table>
<thead>
<tr>
<th>Believe opponent is</th>
<th>Ambiguity Neutral</th>
<th>Ambiguity Averse</th>
<th>$p$-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low Risk Aversion</td>
<td>X: 75%</td>
<td>X: 85%</td>
<td>$p = 0.895$</td>
</tr>
<tr>
<td></td>
<td>Y: 25%</td>
<td>Y: 15%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>N= 56</td>
<td>N= 20</td>
<td></td>
</tr>
<tr>
<td>High Risk Aversion</td>
<td>X: 65%</td>
<td>X: 59%</td>
<td>$p = 0.481$</td>
</tr>
<tr>
<td></td>
<td>Y: 35%</td>
<td>Y: 41%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>N= 20</td>
<td>N= 17</td>
<td></td>
</tr>
<tr>
<td>Any Risk Aversion</td>
<td>X: 72%</td>
<td>A: 73%</td>
<td>$p = 0.567$</td>
</tr>
<tr>
<td></td>
<td>Y: 28%</td>
<td>B: 27%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>N= 76</td>
<td>N= 37</td>
<td></td>
</tr>
</tbody>
</table>

Table 6: Subject’s strategy choice as the column player in the game in figure 6 as a function of the subject’s beliefs of their opponent’s risk and ambiguity preferences, restricted to subjects who passed the comprehension test for the relevant games. The $p$-values are calculated via a directional Fisher’s exact test with null hypothesis that the distribution of behaviour is identical for subjects that believe their opponent is ambiguity neutral and subjects that believe their opponent is ambiguity averse.

20Although not explicitly reported in table 6, the difference in behaviour between subjects who believe their opponent to have low risk aversion and subjects who believe their opponent to have high risk aversion is not statistically significant.
5 Unpacking the results: A new treatment

In the previous section we provided evidence that a subject’s own preferences affects their behaviour in the main testing game in the expected fashion but their beliefs over their opponent’s preferences do not affect their behaviour. A potential explanation for this pair of results is that subjects had a low degree of confidence in their predictions of their opponent’s behaviour. To test this hypothesis, we ran a very simple new treatment: instead of eliciting a subject’s beliefs over their opponent’s preferences, we simply inform the subject of the choices that their opponent made in the preference measuring games. The results are stark: knowledge of your opponent’s preferences is strongly correlated with behaviour as the column player in the main testing game.

For the additional treatment, 91 new subjects were recruited and bought to the ELVSE lab in January 2015. The sessions lasted between 30 and 40 minutes and average earnings were C$22.32. Each subject was matched with an opponent from the original experimental sessions, with the subject’s opponent being selected in a pseudo-random fashion.

Each subject was shown the choice made by their opponent in both the risk and ambiguity measuring games (i.e. their opponent’s choice as the row player in the games in figures 2 and 5). Subjects were also given a summary of their opponent’s performance on the comprehension tasks. The pool of opponents was heavily skewed towards opponents who had performed well on the comprehension tasks – the goal was not to investigate how a subject responded to their opponent’s comprehension score, but rather to provide the subject with a credible signal that their opponent’s choices represent reasoned decisions and not random behaviour generated by a poor understanding of the underlying game.

After subjects had viewed their opponent’s choices in the preference measuring tasks, the subject was asked to play the main testing game as the column player. The matching protocol was explained to subjects with the aid of the diagram in figure 7. The subjects were also required to fill in the drop down menu comprehension questions, and could earn up to $1 in bonus. As in the main treatment, we exclude subjects who performed poorly on the comprehension questions: 83 of the

---

21 There were actually 92 subjects, but one subject had already participated in the original treatment and was therefore excluded from the data reducing the number of data points to 91. The subject had created two accounts in ORSEE, which wasn’t noticed until after the session had finished.

22 No two subjects faced the same opponent, and the pool of subjects was chosen in a manner that was designed to provide better statistical power than would have been provided using true random sampling. Subjects were informed that they were to be matched with a previous experimental participant, but were not given any information regarding how their opponent was selected.
Figure 7: The matching protocol diagram, as shown to subjects. The subject was designated "You", and the subject’s opponent was designated "Counterpart". Arrows are used to represent strategic interactions: the originator’s choice influences the target’s payoff. Note that the subjects were shown a transposed version of the game in figure 6, so the row and column labels are reversed.

91 subjects answered the comprehension questions correctly on their first attempt, the remaining 8 subjects are excluded from the data analysis.  

<table>
<thead>
<tr>
<th>Rationalizability Prediction</th>
<th>Column Player Action</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>X</td>
<td>Y</td>
<td></td>
</tr>
<tr>
<td>{X}</td>
<td>28 (93%)</td>
<td>2 (7%)</td>
<td></td>
</tr>
<tr>
<td>{X, Y}</td>
<td>29 (55%)</td>
<td>24 (45%)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>57 (69%)</td>
<td>26 (31%)</td>
<td></td>
</tr>
</tbody>
</table>

Table 7 summarises the results from this new treatment. It is clear that knowledge of an opponent’s preferences has a strong effect on behaviour as the column player in the game in figure 6; over 90% of the subjects who have a unique rationalizable strategy play that strategy. The effect is both intuitive and as predicted by theory.  

Table 7 summarises the results from this new treatment. It is clear that knowledge of an opponent’s preferences has a strong effect on behaviour as the column player in the game in figure 6; over 90% of the subjects who have a unique rationalizable strategy play that strategy. The effect is both intuitive and as predicted by theory.  

For the comparable game in the main treatment 179 of 206 subjects answered the comprehension questions correctly on the first attempt. The difference (91% vs. 87%) is not statistically significant. Interestingly, however, the Full types are not best responding to the empirical distribution of behaviour of the row player: conditional on any information about an opponent’s preferences (even if the opponent is both risk and ambiguity averse) the empirical best response for the column player is to play X.
Opponent’s preferences | Ambiguity Neutral | Ambiguity Averse |
------------------------|-----------------|----------------|
Low Risk Aversion | X: 93% | X: 93% |
| Y: 7% | Y: 7% |
| N= 30 | N= 14 |

High Risk Aversion | X: 56% | X: 30% |
| Y: 44% | Y: 70% |
| N= 16 | N= 23 |

Any Risk Aversion | X: 80% | X: 54% |
| Y: 20% | Y: 46% |
| N= 46 | N= 37 |

Table 8: Subject’s strategy choice as the column player in the game in figure 6 as a function of their subject’s risk and ambiguity preferences, restricted to subjects who passed the comprehension test for the relevant games. The $p$-values are calculated via a directional Fisher’s exact test with null hypothesis that the distribution of behaviour is identical for subjects whose opponents are ambiguity neutral and subjects whose opponents are ambiguity averse.

Table 8 presents an overview of the data for this ‘knowledge’ treatment, and makes it clear that the effect of knowledge of an opponent’s preferences is being driven by knowledge of the opponent’s risk aversion (rather than ambiguity aversion). For subjects with a risk neutral opponent there is no effect of knowledge of their opponent’s ambiguity preferences, while for subjects with an ambiguity neutral opponent there is a large effect of knowledge of their opponent’s risk preference. Although, as seen in the bottom row of table 8, there is a statistically significant effect of knowledge of an opponent’s ambiguity preference when aggregated over all risk preferences it is a purely spurious relationship that is generated by the large effect of knowledge of an opponent’s risk preferences and correlation between risk and ambiguity preferences.

The non-effect of knowledge of an opponent’s ambiguity preference on behaviour may be an artifact of the experimental design. The payoff structure that was used in the preference measuring games was designed for the original treatment in which an unobserved variable (the subject’s true preferences) was expected to influence behaviour in both the preference measuring games and the testing game. As a consequence, we would expect the results in the original treatment to persist independently of whether the subject understood the relationship between the preference measuring games and the testing game. In the knowledge treatment, however, we will only observe the predicted effects when the subject understands the relationship between games.

It is, of course, unrealistic to think that subjects will have knowledge of the formal relationship between risk preferences, ambiguity preferences and solution concepts across games. There are,
however, some obvious and intuitive patterns that subjects may recognize. For example, in the risk measurement game (figure 5) it is clear that, in laymen’s terms, strategies \( L \) and \( I \) are “risky”, and strategy \( H \) is “safe”. In the testing game (figure 6) it is also clear that strategies \( A \) and \( B \) are “risky”, and strategy \( C \) is “safe”. If an opponent is observed to be willing to take risks in one situation, then it seems reasonable to suppose that they might take risks in another situation.

For the ambiguity measurement game (figure 2) the situation is less clear. Strategy \( S \) is a “riskier” choice than strategy \( M \), but the difference is very slight. Therefore, even if you observe that your opponent has chosen \( M \) you may still quite reasonably believe that they would be willing to choose either \( A \) or \( B \) in the testing game. Things are even murkier when we consider the subjects that observed their opponent choosing either \( L \) or \( I \) in the risk measurement task and choosing \( M \) in the ambiguity measurement task. What is the subject to conclude from this? From the risk task it seems sensible to conclude that the opponent is willing to take risks when the potential reward is large enough (a few dollars), and from the ambiguity task it seems sensible to conclude that the opponent is not willing to take risks when the reward is small (a nickel). Under this line of reasoning, it is not surprising that effect of the risk preference comes to dominate the effect of the ambiguity preference.

It is obvious that the results for subjects with risk and ambiguity neutral opponents are very close to the pure strategy Nash equilibrium of the game. A natural follow up question is: are the results for subjects with risk averse opponents also rationalizable by a Nash equilibrium? The answer is yes: the proportion of subjects playing \( X \) when they observe their opponent to be ambiguity neutral but risk averse (9 out of 16 subjects, see Table 8) forms a Nash equilibrium of the game (where row players mix between \( A \) and \( C \)) when the row player has a CRRA utility function with risk aversion parameter \( \rho = 2.81 \). Given that the choice of \( C \) in the risk measurement game implies \( \rho > 1.93 \) the results are consistent with potential equilibrium play at reasonable levels of risk aversion.

6 Discussion

This section provides a discussion of the results. We begin by dismissing some alternative explanations for the observed behaviour, before placing the results in the context of some previous experiments on epistemic game theory and finishing with some suggestions for future work.
6.1 Other potential explanations of behaviour

There are, of course, other models which could be used to try and rationalize the data presented in section 4. In this section we discuss the implications of level-k models, models of other regarding preferences and quantal response equilibrium (QRE) for the games studied in this paper.

The level-k model (applied with risk neutral SEU preferences, as is standard, see Costa-Gomes and Crawford (2006) for a canonical example) does not describe the results well: because strategy $C$ in the game in figure 6 is dominated, it should never be played by any type of level-1 or higher. Similarly, the strategy $M$ in the ambiguity preference measuring game (figure 2) should also never be played by a non level-0 subjective expected utility agent. The data indicates clear violations of these predictions. A modified version of the level-k model which allows for ambiguity averse preferences may, however, be able to rationalize the data although testing such a model is not the intention of this paper.

Another preference structure that has a strong track record is that of empirical predictions is other-regarding preferences. In models of other-regarding preferences, such as the inequity aversion model of Fehr and Schmidt (1999), agents have preferences that depend both on their own monetary outcome and the monetary outcome of other agents. It is possible, in the main testing game (figure 6), for models of other-regarding preferences to introduce new equilibria. For example, if the row player has very strong other regarding preferences then $(C,Y)$ may be sustained as an equilibrium even for risk neutral ambiguity neutral agents. This would require that the agent prefers receiving $18 while their opponent earns $22 over receiving $25 while their opponent earns $12; while preferences this strong are possible, it seems unlikely that they would be held by more than a small proportion of subjects. It seems, therefore, rather implausible that inequality aversion could be driving the results for the game in figure 6.

For the ambiguous prisoner’s dilemma, discussed in the appendix and shown in figure 9, inequality aversion may help to explain the results. For an ambiguity neutral, risk neutral agent with other regarding preferences the cooperative outcome may be sustained in equilibrium when an agent prefers both them and their opponent to earn $19 over a lottery that pays either $30 or $14 with equal probabilities while their opponent earns nothing. This is a much more modest level of inequality aversion (when an agent has more money than their opponent they prefer their opponent to receive an extra $19 instead of receiving, on average, an extra $3 themselves) and this may be a reason that behaviour in the ambiguous prisoner’s dilemma was so similar to behaviour in previous one-shot prisoner’s dilemma experiments, with almost 40% of subjects choosing the...
cooperative option.

Quantal response equilibrium, in its standard form, cannot rationalize the results of this experiment. Consider the risk measurement game: for the row, player the expected value of each strategy is independent of the column player’s behaviour, and the expected values are ranked $EV(A) > EV(B) > EV(C)$. The average subject observed in the experiment chose $C$ more often than $B$ violating the property of QRE that asserts that strategies with higher expected values are chosen more often. A more sophisticated version of QRE, that allows for variation in risk and ambiguity preferences, may explain the data in this paper. Such a model is left for future work, as the data set in this paper is unlikely to be rich enough to identify the distribution of preferences and the standard QRE parameter simultaneously.

6.2 Uncertainty over preferences and strategies

The results of this paper hint at an epistemic interpretation of the data, although the structure of the game that allows for a separation of preferences from beliefs also limits the conclusions that can be drawn. This section places the results in context with some previous experimental literature on epistemic game theory and points towards future research directions.

Kneeland (Forthcoming) finds, in a paper that focuses on level-k reasoning (rather than ambiguity aversion), using a neat ring-game structure, that while most subjects (94%) are rational they are terrible at forming consistent conjectures regarding each other’s behaviour. Kneeland also finds that a large proportion of subjects believe their opponent’s are rational (72%) and that 44% have second-order beliefs regarding the rationality of others. The results in this paper are not incompatible with Kneeland (Forthcoming): rationality here is somewhat lower (but rationality is identified using a mixed-strategy dominated strategy here, rather than a pure-strategy dominant strategy in Kneeland (Forthcoming)), equilibrium rates are much higher (but the game here is dominance solvable so that consistent conjectures are not required)\textsuperscript{25}, and belief of opponent’s rationality is much higher (in the treatment where subjects were told their opponent’s preferences).

Healy (2013) also provides empirical evidence regarding the epistemic status of laboratory subjects.\textsuperscript{26} One of his main finding is that subjects are generally poor at estimating their opponent’s preferences over outcomes. Here, we find evidence that subjects are very much aware that they are

\textsuperscript{25}The equilibrium analysis is not included in the final published version of Kneeland (Forthcoming), but can be found in earlier working paper versions.

\textsuperscript{26}Healy (2013) is a very interesting paper, on multiple dimensions. It is an incredibly ambitious design, which produces some remarkable data, and the author makes it very clear that the results should not be take too seriously.
poor at estimating their opponent’s preferences: once we show a subject their opponent’s preferences, their behaviour snaps into line with theory implying that out of equilibrium behaviour may have been a response to uncertainty over their opponents preferences.

The results in this paper, and the previous research discussed above, leaves a key open question: what is the best approach to modeling uncertainty in games? The behaviour of row players in the main testing game, presented in figure 1 in the introduction, demonstrates the importance of ambiguity preferences and strategic uncertainty. On the other hand the behaviour of column players, both within the original treatment and across treatments, suggests that modeling preferences as private information is also important. The work of Kneeland (Forthcoming) and Healy (2013) suggests that uncertainty over higher level belief hierarchies may also be important. Grant et al. (2013) takes a first step towards synthesizing some of these ideas in a general theoretical framework although the topic remains largely unexplored.

6.3 Conclusions

This paper presents evidence that both risk and ambiguity preferences play a role in determining behaviour in normal form games, but that beliefs over an opponent’s preferences do not influence behaviour in games. As demonstrated in a follow up treatment, subjects have a high level of uncertainty regarding their opponent’s preferences; when informed of their opponent’s preferences, subjects behaved in a fashion that is largely consistent with equilibrium play. The results suggest that both strategic uncertainty and uncertainty regarding an opponent’s preferences play an important role in determining behaviour in normal form games. Additionally, this paper presents evidence, using discrete choice tasks, that ambiguity and risk preference are correlated.

The results in this paper present support for continuing efforts to expand and refine equilibrium concepts that allow for ambiguity aversion, and for the study of the affects of ambiguity aversion in applied settings. In particular, approaches that allow for both strategic and preference uncertainty appear to be particularly important. In particular, the experimental evidence presented here that strategy choice is correlated with ambiguity preference provides a strong justification for the continued study of the effects of ambiguity aversion in real world settings.
References


Soo Hong Chew, Mark Ratchford, and Jacob S. Sagi. You need to recognize ambiguity to avoid it. 2013.


A Experimental Methodology Appendix

In every experimental design there are a myriad of decisions that the experimenter must make. This section discusses some of the more important choices that were made in the design of this
experiment. The focus is on issues that are likely to be less familiar to readers, rather than standard experimental practices such as ensuring payments are anonymous.

A.1 Piloting and framing effects

This experiment has two distinct sections. First, we measure the subjects preferences and beliefs over their opponent’s preferences. Second, we give the subjects a variety of normal form games. Normal form games are normally presented to subjects in a bi-matrix format. In contrast, decision theorists use a range of procedures to measure preferences, none of which are bi-matrices. A natural concern is that the framing of the task might affect the measurement and it turns out that this concern is well founded. In a series of pilot experiments, we observed that the proportion of subjects that display ambiguity aversion is significantly higher when the task is presented as a worded decision problem (when compared to a bi-matrix game).\(^{27}\)

The existence of a framing effect precludes presenting the preference measurement tasks and normal form games in differing formats. To resolve this problem, we presented all tasks as games. As we are interested in measuring both a subject’s own preferences and their beliefs regarding their opponent’s preferences, we formulate the decision problems as a game where the row player reveals their own preferences and the column player attempts to predict the row player’s behaviour.

A natural concern is that, by moving the preference measurement tasks into a game format, our preference measures will be distorted relative to previous research on ambiguity aversion. The pilot experiments suggested that adding a series of comprehension questions, as described in the next section, does a reasonable job of reducing the gap between worded decision problems and bi-matrix games.\(^{28}\)

A.2 Comprehension questions

On the experimental screen, underneath each of the normal form games, a series of dynamic drop down menus were included for each game. Before a subject could confirm their strategy choice in a game, they were required to fill in the drop down menus correctly. To ensure that subjects took

\(^{27}\)Similar evidence of framing effects for ambiguity aversion measurement can be found in Chew et al. (2013).

\(^{28}\)Despite the inclusion of the comprehension questions, the measured level of ambiguity aversion is still slightly lower than that measured in previous 2-colour Ellsberg urn experiments. The results reported here do appear to be consistent with recent evidence from Chew et al. (2013), who argue that we should expect to measure less ambiguity aversion in more complex environments.
the drop down menus seriously they were paid a bonus of $1 for each game where they filled in the drop down menus correctly on their first attempt. Each incorrect attempt reduced the bonus payment, for that game, by $0.25.

The drop down menus were designed in such a way that the subjects recreated the worded decision problem that describes the relevant game. For example, for the game in figure 2, the worded problem for option A would read “Your earnings for this choice [are/are not] affected by your counterpart’s strategy. Your earnings for this choice will be [$30.10/$30/$15/$0] if a red ball is drawn from the [U urn/K urn] and nothing otherwise.” For each set of terms that are square bracketed, the subjects were required to select the correct (in bold here) term from a drop down menu.

Subjects were required to fill in drop down menus that described the possible outcomes for each of their strategies. The process of interpreting the bi-matrix game and converting it into a worded decision problem helped to ameliorate the framing effects induced by the bi-matrix game.

In addition, the drop down menus also served as a comprehension check. This test of subject comprehension was quite stringent. There were a handful of subjects who had extreme difficulty with the drop down menus, and only 25% of subjects earned the maximum possible bonus payment of $7. We used the level of bonus payment earned by the subject as a measure of comprehension, and removed subjects who performed poorly from our sample.

Given the extensive piloting process, and experimenter degrees of freedom involved in using the comprehension data to exclude subjects, the possibility of data mining for statistically significant results needs to be addressed. Two approaches were taken to alleviate these concerns. First, pilot sessions were run using only the classification games of section 3.1, and not the testing games of section 3.2. Second, the rules for excluding subjects from the data, based on comprehension scores, were determined ex-ante rather than ex-post.

Two rules for excluding subjects were determined ex-ante. A strict rule, and a relaxed rule.  

---

29 In one set of pilot sessions subjects were required to fill in the drop down menu only for the strategy that they selected. This approach was soon abandoned, as it turned out that subjects were making their decisions without referring to the drop down menus, and then only filling in the drop down menus after they had already come to a decision. The drop down menus thereby failed to break down the framing effect of presenting the choices in a bi-matrix format.

30 The only exceptions to this were the first two pilot sessions which used a 3-colour Ellsberg urn instead of the 2-colour Ellsberg urn used in the final design. Only 1 out of 14 subjects was found to be ambiguity averse, meaning that it was not possible to perform any tests on the effects of ambiguity aversion on behaviour, and the 3-colour Ellsberg urn was removed from the design.
There was an expectation that the strict rule may be too strict, so the relaxed rule was designed as a back up. The expectations were correct, and after applying the strict rule only 8 ambiguity averse and risk neutral subjects remained (and only 4 risk averse and ambiguity neutral subjects); therefore, the relaxed rule was used. The comprehension data is reported in further detail in appendix C.3.

The strict rule required that the subjects had earned the full $7 in bonus payments. The relaxed rule required that, for each statistical test, only subjects which earned the full $1 bonus payment for each game used in the construction of that statistical test were included. As an example, the key result linking preferences and behaviour in the game in figure 6 (results of which are displayed in table 3) was constructed using only subjects which earned the full $1 bonus payment as the row player in each of the games in figures 2, 5 and 6.

A.3 A note on learning

It has become standard in experimental economics to allow for subjects to play a game repeatedly, and to argue that subjects will learn the payoff of the structure through experiential learning. Under this approach any initial confusion can be removed from the data by discarding the first few periods of play. Unfortunately this approach is not feasible for experiments that investigate the effects of ambiguity aversion in normal form games. If we allow subjects to learn via repeated play of the game then the subjects may also learn about the distribution of opponent behaviour in the subject population, thereby reducing or eliminating any uncertainty regarding opponent’s behaviour. Repeated play (even against randomized opponents, so that there are no super-game effects) may actually change the equilibrium set for ambiguity averse equilibrium concepts.

Given that we cannot use experiential learning for this experiment, the use of comprehension questions to test for understanding becomes even more important. Subjects who do not pass the comprehension tests on the first attempt may struggle to internalize the payoffs of the game without going through an experiential learning process, and their responses should be considered suspect and removed from the data set.

A.4 Order of realization of randomizations

As discussed in section 2, many models of ambiguity aversion induce preferences with a strict preference for randomization. In an experiment, such as this one, where we are asking subjects
to respond to multiple games there are two ways in which a preference for randomization could undermine the incentive structure. In both cases, however, the results of Eichberger et al. (2014) (and similar ideas found in earlier papers, dating back to at least Kreps (1988)) can be used to overcome any concerns: if objective randomizations occur before subjective states are realized then dynamic consistency implies no preference for randomization. We maintain, without apology, an assumption of dynamic consistency throughout this paper.

The first difficulty, as discussed in section 2, occurs within a game. If subjects have a strict preference for randomization then the availability of mixed strategies can change the equilibrium set (relative to the game where only pure strategies are available). The strict preference for randomization can be negated via two arguments. First, subjects were required to select pure strategies in each of the games (i.e. the computer interface did not allow for mixed strategies to be chosen explicitly). In order to play a mixed strategy subjects would need to provide their own randomization device, whether it be a mental mixing, tossing of a coin or rolling of a die. Second, following the arguments of Eichberger et al. (2014) there should be no preference for randomization if a subject’s own randomization is resolved before they view their opponent’s strategy choice. This requirement was satisfied during the experiment as a consequence of requiring subjects to enter pure strategy choices into the computer, and not revealing their opponent’s strategy choices until the end of the experiment.

The second difficulty occurs between games. If subjects have a strict preference for mixing between games, then using a random payment mechanism31 will provide the subject with an opportunity to hedge their ambiguity across games and they will not treat each game as an independent decision problem. On the other hand, paying subjects for their decisions in all games will obviously give rise to hedging opportunities across games, particularly given that several of the games include a draw from an Ellsberg urn that determines the ‘play’ of nature. Baillon et al. (2014) provides some solace, and a joint reading of Azrieli et al. (2014) and Eichberger et al. (2014) reinforces this view. Baillon et al. (2014) demonstrate that if objective randomizations are resolved after subjective randomizations then the elicitation is not incentive compatible; if subjective randomizations are realized first then incentive compatibility may be restored. Azrieli et al. (2014) suggest that, absent an assumption that subjects are indifferent between ex-ante and ex-post randomizations, there are no strong objections to be made against using a random payment mechanism in an experiment of this nature. Following this, it is clear from Eichberger et al. (2014) that the random payment

---

31A random payment mechanism chooses, at random, a subset of the tasks in the experiment to be the tasks for which subjects are actually paid. Usually, the number of tasks that are selected is one, and this is sometimes referred to as a “pay-one” incentive scheme.
mechanism should be resolved prior to the resolution of play in the games. Furthermore, John-
son et al. (2014) demonstrate experimentally that an elicitation process which they call PRINCE,
including this order of realizations, can improve the quality of elicited preferences.

Resolving the random payment mechanism prior to the resolution of play in the games requires
some care. It is obviously not appropriate to allow the subjects to know which game will be chosen
for payment before the subjects play the games. The solution implemented here was as follows:
when subjects entered the experimental lab there were 7 flash cards stuck to one of the walls. On
the front (visible to subjects) side of the flash cards were the letters A through G, one letter per
flash card. On the back (not visible to subjects) were the numbers 1 through 7, one number per
flash card. The matching of letters to numbers was randomly determined by the experimenter.32
During the instructions, a subject was asked to choose a letter from A to G, and the number was
recorded. Subjects were informed that, at the end of the experiment, the number on the back of
the chosen letter would determine which game would be paid. From the subjects perspective the
choice of game was then fixed, but unknown. At the end of the experiment, the letter was flipped
over to reveal the game to be paid before any balls were drawn from the urns.

All randomizations and ball draws were conducted using physical devices that were as proce-
durally transparent as possible.

A.5 Related experimental literature

There is very little experimental evidence regarding ambiguity aversion in game theory. There
are, as far as I am aware, only a handful of papers that have collected experimental data that was
designed to investigate ambiguity aversion in game theory (Kelsey and le Roux (2015a), Kelsey and
le Roux (2015b), Ivanov (2011), Eichberger et al. (2008), Pulford and Colman (2007), and Camerer
and Karjalainen (1994)).33 There is one additional paper that re-analyses previous experimental
data (Eichberger and Kelsey (2011)). We proceed chronologically.

Camerer and Karjalainen (1994) present evidence from 4 games. The first two games are
designed to replicate the standard Ellsberg tasks, but replacing the subjective ball draw with a
choice by an opponent. The third game requires subjects to predict the outcome in a co-ordination
game that had previously been played by other subjects. In each of these games Camerer and

32There were actually two sets of flash cards, one with letters and one with numbers. Letter flashcards were then
randomly blu-tacked to number flashcards. This enabled the flash cards to be easily re-randomized between sessions.
33Di Mauro and Castro (2011) study a voluntary contribution game where subjects play against virtual agents. It
is debatable whether this should be viewed as a game, or simply a specially structured decision problem.
Karjalainen found, on average, a consistent yet small amount of ambiguity aversion along with a large amount of heterogeneity between subjects. These games, however, do not really have strategic interaction in a meaningful sense; in each game the strategic uncertainty only affects one of the players.

The fourth game that Camerer and Karjalainen study is a matching pennies game with an extra risky option for the row player. This is a very clever design that allows the row player to, effectively, choose between a bet on their opponent’s strategy choice or a bet on a random draw. Again, the average subject was measured to be ambiguity averse.

Pulford and Colman (2007) took an approach that is somewhat opposed to that of Camerer and Karjalainen (1994). In Pulford and Colman (2007) subjects faced either a complete information game where their opponent was completely indifferent between all outcomes, or a game of incomplete information where their opponent had one of two types and each type of opponent had a differing dominant strategy. Pulford and Colman argue that the complete information game is a risky game and the incomplete information game is an ambiguous game (when subjects were not informed about the probability distribution of types).

Pulford and Colman argue, using the principle of insufficient reason, that the only reasonable beliefs are that an opponent who is indifferent everywhere should be expected to choose each strategy precisely half the time. This assumption is very strong. A weaker, more reasonable, assumption would be that we require beliefs in this case to be symmetric (but possibly non-additive). Under this alternative assumption it becomes very difficult to interpret the results of Pulford and Colman (2007).

Eichberger et al. (2008) is a very entertaining paper. Subjects played a variety of normal form games against either a granny, a game theorist, or another subject. Eichberger et al. hypothesized, and it was confirmed in the data, that subjects would view playing against the game theorist as being less ambiguous than playing against the granny.34 There was no evidence of any differences in behaviour between subjects playing against the granny or against another subject.

Eichberger et al. structured their games in a manner which allowed the ambiguity involved in a game to be quantified. Fixing the identity of the opponent, it was usually the case that subjects played the Nash equilibrium strategy less in games with higher levels of ambiguity.35

34 Personally, I find this result to be surprising. My prior was that undergraduates would feel more comfortable predicting the behaviour of a granny than a game theorist, given that most undergraduates would presumably have spent more time interacting with grannies than game theorists.

35 The exceptions occurred for subjects that were playing the game theorist.
The results in Eichberger et al. (2008) are clearly consistent with ambiguity averse behaviour. Eichberger and Kelsey (2011) revisit the data from Goeree and Holt (2001), and establish that the data is also broadly consistent with ambiguity averse behaviour. The analysis in both papers is, however, at the aggregate level and there are other theories and heuristics that could rationalize the results. Given the large amount of between subject heterogeneity that has been observed in decision theory ambiguity aversion experiments (see Halevy (2007) for example), it seems that tracking individual subject level behaviour across games would be a natural next step.

Ivanov (2011) takes this next step. He uses a considerably more complicated design, and makes extensive use of stated beliefs in his identification process. First, subjects played a series of normal form games. Next, subjects were asked to state their beliefs regarding their opponent’s behaviour in the normal form games. Finally, subjects were asked to choose between lotteries that were constructed from their beliefs in part two and the payoffs from the games in part one.

The central question posed in Ivanov (2011) is quite different from the questions raised in this paper. Ivanov seeks to classify subjects as ambiguity averse/ambiguity neutral/ambiguity loving using only their responses to normal form games; the headline result is that 22/46/32 percent of subjects fall into each category, respectively. Unlike Ivanov (2011), this paper does not consider ambiguity seeking behaviour (ambiguity seeking subjects will be indistinguishable from ambiguity neutral subjects). On the other hand, Ivanov (2011) requires an assumption that stated beliefs are equal to true beliefs in order to identify ambiguity preference, whereas the current paper measures ambiguity preference directly.

Kelsey and le Roux (2015a) is the only other paper that compares behaviour in Ellsberg urn tasks to behaviour in normal form games at the individual level. The results reported in Kelsey and le Roux (2015a) are mostly negative, however. They find significant levels of ambiguity aversion in their normal form game (a battle of the sexes game augmented with a safe option for the column player), but find much less ambiguity aversion (and even some ambiguity seeking) in their Ellsberg urn tasks. This contrasts with the results here, where Ellsberg urn behaviour was correlated with behaviour in the game in figure 6.

There are three potential reasons for the differences in results between the two papers. Firstly, Kelsey and le Roux (2015a) do not control for risk aversion. The behaviour in their normal form game might be driven by risk aversion, rather than ambiguity aversion. Secondly, Kelsey and le Roux (2015a) also asked for stated beliefs, but they did not put them to work in the fashion of Ivanov. In one treatment beliefs were elicited at the same time as the games were played. If we model ambiguity aversion using the MEU model, then the notion of ‘true beliefs’ need not be well defined.
le Roux (2015a) used a three-colour Ellsberg urn, rather than the two-colour Ellsberg urn used here. Chew et al. (2013) report that measured levels of ambiguity aversion are often much lower in two-colour rather than 3-colour Ellsberg tasks. The reasons for this difference are not exactly clear, although Chew et al. argue that it is a confusion effect (that subjects do not recognise the 3-colour urns as being ambiguous).

The third difference between Kelsey and le Roux (2015a) and the current paper is the use of comprehension questions. The results of Chew et al. (2013) suggest that, in some situations, subjects will have trouble recognizing and responding to ambiguity. To ensure that this does not affect results, we used a series of drop down menu comprehension questions to screen for understanding. Kelsey and le Roux (2015a) did not use any tests for comprehension, and this may make it harder to identify a relationship between ambiguity averse behaviour in the games and ambiguity averse behaviour in the Ellsberg tasks.

The identification of the link between individual choice tasks and normal form game behaviour is always going to be difficult because the Nash equilibrium remains an equilibrium for ambiguity averse subjects. This implies that even in ideal circumstances the power of a test to reject the null hypothesis of independence may be low (particularly if the Nash equilibrium is focal). Although, as demonstrated in this paper, the effect can be recovered with a clean experimental design. On balance, the evidence strongly suggests that ambiguity aversion has an influence on behaviour in normal form games.

B Theory Appendix

There is a growing literature that models the extension of game theory to subjects with non-neutral ambiguity preference. There is, however, surprisingly little agreement on how to proceed. Should an ambiguity averse equilibrium concept maintain mutual knowledge of rationality? Should stochastic independence be preserved, or should we allow for correlation between agent’s strategies? How much (if at all) should consistency of beliefs be relaxed? Each of these questions could be used to categorize the literature in various ways. We focus, instead, on the role of mixed strategies for the reasons discussed in the main text.

To reiterate, there are three ways for the game theorist to proceed. Either allow agents to hold

---

39 In piloting for this experiment, two sessions were run using a 3-colour Ellsberg urn. Only 1 out of 14 subjects was classified as being ambiguity averse. Given this extremely low observed rate of ambiguity aversion, 3-colour Ellsberg urns were not used in any other sessions.
strict preferences for mixed strategies, restrict the strategy space to contain only pure strategies (and thereby avoid the issue altogether), or to place restrictions on the model such that the agent does not have a strict preference for mixed strategies. Models that fit the third category require careful attention to be paid regarding the timing of realizations of randomization devices. Currently, the only two papers that have used the third approach have not been sufficiently careful (Rothe (2010) and Lehrer (2011)). Table 9 provides a summary of the state of the literature.

As can be seen in table 9 a majority of the literature simply excludes mixed strategies. The experimental design in this paper could be reinterpreted using any of the equilibrium concepts that exclude mixed strategies. It is not, however, compatible with models that allow a strict preference for randomization, such as Lo (1996) or Bade (2011).\textsuperscript{40} For example, propositions 4 and 5 in Lo (1996) imply that for two-player games with a unique strict pure strategy Nash equilibrium, such as the game in figure 6 here, the only ambiguity averse equilibrium is the Nash equilibrium. Bade (2011) gives agents access to an ambiguous randomization device (i.e. agents can condition their strategy on a draw from an Ellsberg urn, for example), but finds observational equivalence between Nash equilibria and ambiguity averse equilibria in two-player games.

Returning to the questions raised in the opening paragraph of this section, in the opinion of this author, the most convincing answers have been provided by Lo (2009). Lo posits an epistemic approach to ambiguity averse game theory; beginning with the epistemic conditions of Nash equilibrium, what are the consequences of relaxing rationality to allow for ambiguity averse preferences? The resultant equilibrium concept substantially relaxes stochastic independence\textsuperscript{41}, allows agents to hold set valued beliefs regarding their opponent’s strategies and requires actual play to lie within the set of beliefs, and maintains mutual knowledge of rationality.

The only desiderata missing from Lo (2009) is that it does not allow for mixed strategies; the strategy space is restricted to pure strategies, and a population interpretation of mixing is invoked. In a related paper, Calford (2015), the current author extends Lo (2009) to allow for mixed strategies.

\textsuperscript{40}To be more precise, the mapping from preferences to strategies embodied in the hypotheses tested in section 4 does not hold for some models of ambiguity aversion. The experimental results presented in this paper could be interpreted as providing some evidence against models such as Lo (1996) or Klibanoff (1996). An alternative viewpoint would be to argue that a proper test of these papers would require an explicit mixing device be provided to subjects. Similarly, a proper test of Bade (2011) would require subjects to have access to an ambiguous mixing device.

\textsuperscript{41}In fact, Lo refers to his equilibrium as Correlated Nash equilibrium to emphasize the similarities with Aumann’s Correlated equilibrium. We avoid using this name, and instead refer to the equilibrium as Lo-Nash equilibrium, to avoid confusion between the two concepts.
<table>
<thead>
<tr>
<th>Paper</th>
<th>Equilibrium concept</th>
<th>Treatment of mixed strategies</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lo (1996)</td>
<td>Belief equilibrium</td>
<td>Strict preference for mixed strategies allowed</td>
</tr>
<tr>
<td>Epstein (1997)</td>
<td>Rationalizability</td>
<td>Pure strategies only</td>
</tr>
<tr>
<td>Lo (2009)</td>
<td>Lo-Nash equilibrium</td>
<td>Pure strategies only</td>
</tr>
<tr>
<td>Dow and Werlang (1994)</td>
<td>Nash equilibrium under uncertainty</td>
<td>Pure strategies only</td>
</tr>
<tr>
<td>Marinacci (2000)</td>
<td>Belief equilibrium</td>
<td>Pure strategies only</td>
</tr>
<tr>
<td>Eichberger and Kelsey (2000)</td>
<td>Equilibrium under uncertainty</td>
<td>Pure strategies only</td>
</tr>
<tr>
<td>Groes et al. (1998)</td>
<td>Nash equilibrium with lower probabilities</td>
<td>Pure strategies only</td>
</tr>
<tr>
<td>Eichberger and Kelsey (2014)</td>
<td>Equilibrium under ambiguity</td>
<td>Pure strategies only</td>
</tr>
<tr>
<td>Klibanoff (1996)</td>
<td>Equilibrium with uncertainty aversion</td>
<td>Strict preference for mixed strategies allowed</td>
</tr>
<tr>
<td>Grant et al. (2013)</td>
<td>Savage games</td>
<td>Pure strategies only</td>
</tr>
<tr>
<td>Lehrer (2011)</td>
<td>Partially specified equilibrium</td>
<td>Mixed strategies have payoffs that are assumed to be linear in utility</td>
</tr>
<tr>
<td>Rothe (2010)</td>
<td>Choquet Nash equilibrium</td>
<td>Mixed strategies have payoffs that are assumed to be linear in utility</td>
</tr>
</tbody>
</table>

Table 9: This table contains summary of the treatment of mixed strategies in the literature of ambiguity averse equilibrium concepts. Only papers that define and introduce equilibrium concepts are included, applications are not included. Note that the approach taken by Lehrer (2011) and Rothe (2010), of assuming that the payoffs of mixed strategies are linear in utility, raises some difficulties that are not addressed in either paper.
B.1 Mixed Strategies

It is well accepted that there are two interpretations of mixed strategies in games: we can interpret a mixed strategy either as a conscious randomization, or as an agent’s belief over the distribution of pure strategy choices of their opponent. The two interpretations are behaviorally indistinguishable when agents have SEU preferences. This equivalence no longer holds, however, when we allow for ambiguity averse preferences.

To see why this equivalence breaks down, it is sufficient to consider an example (from Raiffa (1961)) with a single decision maker. Consider a decision maker who is drawing a ball from an Ellsberg Urn (as shown in figure 3) with 10 balls, each of which is either red or yellow. The decision maker may choose which color to bet on. Raiffa argues that an ambiguity averse agent could benefit from mixing: if the agent were able to flip a coin, and condition their choice of color on the outcome of the coin toss, then they have an (objective) 50% chance of winning the bet. For an ambiguity averse agent, the mixed strategy will be strictly preferred to either of the original prospects.42

Seo (2009) demonstrates that, for agents who violate the reduction of compound lotteries, the above argument hinges critically on whether the objective randomization occurs before or after the ball is drawn from the urn. Furthermore, Halevy (2007) provides experimental evidence that subjects who exhibit ambiguity aversion overwhelmingly do not reduce compound lotteries. Therefore we conclude, for ambiguity averse agents, that the order of realization of randomizations is important.

Additionally, Eichberger et al. (2014) demonstrate that, for a dynamically consistent agent, the agent will be indifferent between the randomization and the initial prospects if the randomization occurs before the uncertainty is resolved (i.e. the coin flip occurs before the ball is drawn), but that Raiffa’s argument may hold if the randomization occurs after the uncertainty is resolved (i.e. the ball is drawn before the coin flip). The reasoning is as follows: if the randomization occurs first, then there is an intermediate stage, after the randomization has occurred but before the uncertainty is resolved, at which the agent is holding one of the original prospects. Strict preference for the randomization implies that the randomization has a strictly higher certainty equivalent than the certainty equivalent for either of the original prospects43, and it would be possible to offer the agent an amount of money (in exchange for foregoing the gamble) that they would reject prior to the

---

42Note that this argument requires that the agents subjective beliefs over the two states (colour of the ball drawn) are symmetric.

43Under the assumption that the agent was indifferent between the two original prospects. The argument can be be modified slightly to accommodate the case where the agent is not indifferent.
randomization but accept at the interim stage, violating dynamic consistency.

Applying this logic to strategic interactions, it is possible for an ambiguity averse agent to strictly prefer a mixed strategy over any of the pure strategies that are in the support of the mixed strategy. There are three ways for the game theorist to proceed. Either allow agents to hold such preferences, restrict the strategy space to contain only pure strategies (and thereby avoid the issue altogether), or to place restrictions on the model such that the agent does not have a strict preference for mixed strategies. As the above arguments suggest, models that fit the third category require careful attention to be paid regarding the timing of realizations of randomization devices. Appendix B provides a brief overview of the current literature; most of the literature takes the second approach of restricting the agents to pure strategies and adopting the population interpretation of mixed strategy equilibria.

### B.2 Lo-Nash equilibria

This section introduces Lo-Nash equilibrium, following Lo (2009) closely. Define a set of players \( N = \{1, \ldots, n\} \), let each player \( i \in N \) have a finite set of actions \( A_i \), and define \( A = \times_{i \in N} A_i \) and \( A_{-i} = \times_{j \neq i \in N} A_j \). We shall endow each agent with a Von Neumann-Morgenstern utility function \( u : A \rightarrow \mathbb{R} \). Suppose that an agent has uncertainty regarding the strategy choices of their opponents, \( A_{-i} \). Then we can regard a strategy, \( a_i \), as an act over the state space \( A_{-i} \) generating a payoff \( u_i(a_i, a_{-i}) \) when the state \( a_{-i} \) is realized.

In a manner consistent with Gilboa and Schmeidler (1989)’s MEU formulation, we suppose that an agent’s beliefs regarding their opponents strategies are a closed and convex set of probability measures \( \Phi_i \subseteq \Delta(A_{-i}) \). Given \( \Phi_i \), an agents preferences are represented by

\[
\min_{\phi \in \Phi} \sum_{a_{-i} \in A_{-i}} u_i(a_i, a_{-i}) \phi_i(a_{-i}).
\]

Furthermore, we use \( \sigma \) to denote a probability measure on \( A \). We define \( \sigma^{A_i}(a_i) = \sum_{a_{-i} \in A_{-i}} \sigma(a_i, a_{-i}) \) as the marginal distribution of \( \sigma \) on \( A_i \) and \( \sigma^{A_{-i}}(a_{-i}) = \sum_{a_i \in A_i} \sigma(a_i, a_{-i}) \) as the marginal distribution of \( \sigma \) on \( A_{-i} \). Then, in the usual fashion we write \( \sigma(a_{-i}|a_i) = \frac{\sigma(a_i, a_{-i})}{\sigma^{A_i}(a_i)} \).

Finally, we write \( \text{supp} \sigma \) to denote the support of the probability distribution \( \sigma \), and define \( \text{supp} \Phi \) to be the union of the supports of the elements of \( \Phi \). We are now ready to define a Lo-Nash equilibrium.
Definition 1 (Lo-Nash equilibrium). A pair $<\sigma, \Phi>$ forms a Lo-Nash equilibrium if it satisfies

$$\sigma(\cdot|a_i) \in \Phi_i \ \forall a_i \in supp \sigma^A_i, \forall i \in N$$  \hspace{1cm} (5)

$$supp \Phi_i = \times_{j \neq i} supp \sigma^A_j \ \forall i \in N$$  \hspace{1cm} (6)

and

$$a_i \in \arg \max \min_{\tilde{a}_i \in A_i, \phi_i \in \Phi_i} \sum_{a_{-i} \in A_{-i}} u_i(\tilde{a}_i, a_{-i}) \phi_i(a_{-i}) \quad \forall a_i \in supp \sigma^A_i, \forall i \in N$$  \hspace{1cm} (7)

Equation 7 requires that all strategies that are played in an equilibrium are best responses, with preferences defined as MEU preferences with respect to the equilibrium conjectures $\Phi$. Equations 5 and 6 are the consistency requirements: equation 6 ensures that a strategy is played with a positive probability iff it is expected to be played with a positive probability, and equation 5 forces actual strategies to be contained in the belief sets. Note that 5 allows for conditioning of $\sigma$ on $a_i$ - this allows for strategies to be correlated, but the realized strategy must lie within player $i$’s belief set for all $a_i$.

B.3 Lo-Nash equilibrium: an example

Consider the normal form game presented in figure 8. For this section, we shall follow the standard game theoretic approach and assume that the payoffs in figure 8 are utility values, thereby abstracting from issues of risk aversion. Recall that the game has a unique Nash equilibrium $(A, X)$.

$$
\begin{array}{|c|c|}
\hline
& Y & \\
\hline
A & 25,20 & 14,12 \\
B & 14,20 & 25,12 \\
C & 18,12 & 18,22 \\
\hline
\end{array}
$$

Figure 8: Main testing game

In contrast, there are fully mixed Lo-Nash equilibria in this game. Intuitively, this is easy to see. If the row player is uncertain about the column player’s strategy choice, and the row player is ambiguity averse, then there are set-valued beliefs for which $C$ is a best response. There does not, however, exist a Lo-Nash equilibrium where the row player plays $C$ with probability 1. The consistency requirements for Lo-Nash equilibria would then imply that the column player would know with certainty that the row player will play $C$, so the unique best response for the column
The source of ambiguity is not from doubts over which Nash equilibrium is to be played, nor is it over which strategy will be realized in a mixed strategy Nash equilibrium. The source of ambiguity in this game is endogenous to the game structure and agent’s preferences. The only requirement is that the row player has
ambiguity averse preferences, so that $C$ is a best response for some potential row player beliefs and thereby breaking the rationalizability chain required to produce the unique $(A,X)$ equilibrium.

As is always the case, the unique Nash equilibrium is also a Lo-Nash equilibrium. Ambiguity averse preferences, on their own, need not necessarily affect the play of a game if the agents still form point-valued conjectures. If an agent believes, with certainty, that their opponent will play a particular (possibly mixed) strategy then there is no role for their ambiguity to play as, subjectively, the agent faces no ambiguity.

The other key feature of the game in figure 8 is that equilibria other than $(A,X)$ exist iff the row player is ambiguity averse (lemmas 4 and 5). If the row player has SEU preferences, then the column player’s ambiguity preference has no effect on the equilibrium set. Using this result, we can differentiate the effect of a players own ambiguity preference (which should affect row player behaviour only) from the effect of a players beliefs about their opponent’s ambiguity preference (which should affect column player behaviour only).

**Definition 2.** A Lo-Nash equilibrium is proper for agent $i$ iff $\Phi_i$ is not a singleton. A Lo-Nash equilibrium is proper iff it is proper for at least one agent.

**Lemma 4.** All proper Lo-Nash equilibrium of the game in figure 8 are proper for the row player.

**Proof of lemma 4.** From lemma 3, all proper Lo-Nash equilibria involve the row player mixing between $C$ and at least one of $A$ or $B$. If the row player has singleton beliefs, then their set of best responses can never include $C$. Therefore, any proper Lo-Nash equilibrium must be proper for the row player.

**Lemma 5.** There exist proper Lo-Nash equilibrium of the game in figure 8 that are not proper for the column player.

**Evidence.** Consider the equilibrium where $\sigma(A,X) = \sigma(A,Y) = \frac{1}{6}, \sigma(B,X) = \sigma(B,Y) = \frac{1}{5}, \sigma(C,X) = \sigma(C,Y) = \frac{2}{5}, \Phi_R = \{\phi : \frac{4}{11} \leq \phi(X) \leq \frac{7}{11}\}$ and $\Phi_C = \{\phi : \phi(C) = \frac{4}{9}, \phi(A) = \frac{1}{3}, \phi(B) = \frac{2}{9}\}$.

**B.4 Nash Equilibrium under Ambiguity**

In this section we describe Dow and Werlang’s (1994) Nash Equilibrium under Ambiguity. The analysis will follow Dow and Werlang (1994) very closely. We begin by introducing the notion of a
sub-additive probability, \( P \), being a probability which satisfies
\[
P(A) + P(B) \leq P(A \cap B) + P(A \cup B).
\]

The expected utility of an agent with respect to a sub-additive probability over a non-negative random variable, \( X \), is given by the Choquet integral
\[
E(X) = \int_{\mathbb{R}^+} P(X \geq x)dx.
\]
In many cases this will be equivalent to calculating the Maxmin Expected Utility with respect to the core of the sub-additive probability (see Gilboa and Schmeidler (1994) for details).

Dow and Werlang define the support of a sub-additive probability to be an event, \( A \), such that \( P(A^c) = 0 \) and \( P(B^c) > 0 \) for all \( B \subset A \). We note that the support need not be unique, and that there are other reasonable definitions of the support of a sub-additive probability that are not used here.

A Nash equilibrium under uncertainty is then simply the requirement that all strategies that are in the support of an opponent’s beliefs are best responses for an agent given the agent’s beliefs. Label the set of available strategies for player \( i \) as \( A_i \).

**Definition 3** (From Dow and Werlang (1994)). A pair \((P_1, P_2)\) of non-additive probabilities \( P_1 \) over \( A_1 \) and \( P_2 \) over \( A_2 \) is a Nash Equilibrium under Uncertainty if there exist a support of \( P_1 \) and a support of \( P_2 \) such that

(i) for all \( a_1 \) in the support of \( P_1 \), \( a_1 \) maximizes the expected utility of player 1, given that \( P_2 \) represents player 1’s beliefs about the strategies of player 2; and conversely,

(ii) for all \( a_2 \) in the support of \( P_2 \), \( a_2 \) maximizes the expected utility of player 2, given that \( P_1 \) represents player 2’s beliefs about the strategies of player 1.

We refrain from giving the full set of equilibrium sub-additive probabilities, as many of them produce observationally equivalent outcomes, but instead establish two facts: that a fully mixed equilibrium can be supported, and that pure \( \{C,Y\} \) can be supported, in a Nash Equilibrium under Uncertainty.

**Lemma 6.** The pure strategy equilibrium \( \{C,Y\} \) can be supported by the equilibrium sub-additive probability \( P_C \) with \( P_C(Y) = \frac{3}{11} \) and \( P_C(X) = 0 \) and additive probability \( P_R \) with \( P_R(C) = 1 \).

**Proof of lemma 6.** The support of \( P_C \) is \( \{Y\} \) and the support of \( P_R \) is \( \{C\} \). It is obvious that \( Y \) is the unique best response for the column player. The row player evaluates their strategies as
follows:

\[
U(A) = 1 \times 14 + 0 \times (25 - 14) = 14 \\
U(B) = 1 \times 14 + \frac{3}{11} \times (25 - 14) = 17 \\
U(C) = 18
\]

\(C\) is the unique best response.

**Lemma 7.** A fully mixed equilibrium can be supported by the equilibrium sub-additive probability \(P_C\) with \(P_C(X) = P_C(Y) = \frac{4}{11}\) and additive probability \(P_R\) with \(P_R(C) = \frac{4}{9}\), \(P_R(A) = \frac{3}{9}\), \(P_R(B) = \frac{2}{9}\).

**Proof of lemma 7.** The support of \(P_R\) is \(\{A, B, C\}\) and the support of \(P_C\) is \(\{X, Y\}\). Given that \(P_R\) is additive we can calculate the column player’s utility in the standard fashion, and verify that \(U(X) = U(Y) = \frac{148}{9} \approx 16.4\). The row player evaluates their strategies as follows:

\[
U(A) = 1 \times 14 + \frac{4}{11} \times (25 - 14) = 18 \\
U(B) = 1 \times 14 + \frac{4}{11} \times (25 - 14) = 18 \\
U(C) = 18
\]

Therefore, both players are indifferent between all strategies in the supports of the distributions.

**B.5 Proofs**

Some of the proofs in this section use the method of iterated elimination of dominated strategies to establish the rationalizable sets. For two player games this method produces results equivalent to the Pearce/Bernheim definition of rationalizability, and Epstein (1997) establishes that the equivalence also holds for agents with MEU preferences.

**Proof of proposition 1.** For the case of SEU preferences the result follows from a straightforward application of Pearce/Bernheim rationalizability.

For the case of MEU preferences we apply the Epstein (1997) notion of rationalizability. We need to find a set of beliefs that rationalizes each possible strategy. For the row player \(\Phi_R = \{\phi : 0 \leq \phi(X) \leq 1\}\) rationalizes \(C\), \(\Phi_R = \{\phi(X) = 1\}\) rationalizes \(A\) and \(\Phi_R = \{\phi(X) = 0\}\) rationalizes \(B\). For the column player \(\Phi_C = \{\phi : \phi(C) = \frac{4}{9}\}\) makes the column player indifferent between each of their strategies, and therefore rationalizes both strategies. All strategies are therefore rationalizable.
Proof of proposition 2. We proceed by modeling the situation as a Bayesian game, treating the two types of row players as distinct players.

In the first round, the SEU type row player eliminates $C$. All other strategies for all other players are best responses.

In the second round, the maximal payoff available to the column player from playing $Y$ is $U(Y) = 22\alpha + 12(1 - \alpha) = 10\alpha + 12$ while the minimum payoff from playing $X$ is given by $U(X) = 12\alpha + 20(1 - \alpha) = 20 - 8\alpha$. Therefore, $X$ dominates $Y$ whenever $\alpha < \frac{4}{9}$, so that $Y$ is eliminated iff $\alpha < \frac{4}{9}$.

A consequence of this is that no more strategies can be eliminated if $\alpha \geq \frac{4}{9}$.

If $\alpha < \frac{4}{9}$, then we must consider the third round. In this case, $Y$ has been eliminated in the third round, and both types of row players now have a unique best response of $A$. Therefore, $\{A, X\}$ is the only rationalizable strategy.

C Results Appendix

C.1 Second testing game: Ambiguous Prisoner’s Dilemma

The second testing game is an ambiguous prisoner’s dilemma, shown in table 9. For risk neutral and ambiguity neutral subjects the game collapses to the standard prisoner’s dilemma with dominant strategies $B$ and $Y$. In fact, to support $(B, Y)$ as the unique equilibrium all we need is for one subject to be risk and ambiguity neutral. To see this, suppose that the row player is risk and ambiguity neutral. Then $B$ is strictly dominant for the row player. Given that the row player will play $B$, $Y$ is the unique best response for the column player, irrespective of their risk and ambiguity preferences.\textsuperscript{44}

If both players prefer 19 for sure over an uncertain prospect that pays 30 in the good state and 14 in the bad, then $(A, X)$ can be sustained in an equilibrium. Because the game in figure 9 is symmetric up to a relabeling of the colours of the balls, we will analyze the data as if everyone played the game as the row player.

For an ambiguity neutral agent, the degree of risk aversion required for $A$ to be an equilibrium strategy is comparable to the degree of risk aversion required in the game in figure 6. The critical

\textsuperscript{44}The analysis here has been somewhat informal. The intuition holds, however, when we treat the game formally. There a few different options for a formal treatment, one of which is being developed in Calford (2015).
value of the utility parameter under CARA utility is the same for both games (to 2 decimal places), and the critical value of the utility parameter under CRRA utility is slightly higher for the game in figure 9 ($\beta = 2.07$ compared to $\beta = 1.93$).

Conclusion 7. Subjects that have high risk or ambiguity aversion (choose B in the game in figure 2 or C in the game in figure 5) and believe that their opponents have high risk or ambiguity (choose Y in the game in figure 2 or Z in the game in figure 5) will have a fully mixed equilibrium in the game in figure 9. All other subjects have a unique rationalizable strategy of B.

C.1.1 Results of the Ambiguous Prisoner’s Dilemma

Given that a subject’s beliefs do not explain behaviour well, it would be surprising if behaviour in the ambiguous prisoner’s was explained well be a subject’s preferences and beliefs. We are not surprised. Table 10 restricts the sample to the 74 subjects that passed the comprehension test for all of the classification games and the game in figure 9.

<table>
<thead>
<tr>
<th>Ambiguous Dilemma Action</th>
<th>A</th>
<th>B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nash</td>
<td>10 (36%)</td>
<td>18 (64%)</td>
</tr>
<tr>
<td>Mixed</td>
<td>15 (33%)</td>
<td>31 (67%)</td>
</tr>
<tr>
<td></td>
<td>25 (34%)</td>
<td>49 (66%)</td>
</tr>
</tbody>
</table>

Table 10: Subject’s equilibrium classification crossed with their ambiguous prisoner’s dilemma strategy choice, restricted to subjects who passed the comprehension test for the relevant games. A subject is classified as a Mixed type if they are either ambiguity averse or have high risk aversion and believe their opponent to be ambiguity averse or have high risk aversion; otherwise the subject is classified as a Nash type. Equilibrium predictions are bold and underlined. Percentages are the cell count as a percentage of the row total. Directional Fisher’s exact test $p = 0.702$.

Result 6. A subject’s preferences and beliefs regarding their opponent’s preferences do not explain behaviour in the ambiguous prisoner’s dilemma

It is interesting to note that the cooperation rate in the ambiguous prisoner’s dilemma (34%)
is comparable to the cooperation rate in the standard one-shot prisoner’s dilemma reported in, for example, Cooper et al. (1996). It is entirely possible that behaviour in the ambiguous prisoner’s dilemma is more closely related to other-regarding preferences (Fehr and Schmidt (1999)) than it is related to ambiguity preferences, particularly given that the sucker payoff is unambiguously bad ($0 in the game in figure 9).

**Result 7.** *Cooperation rates in the one-shot ambiguous prisoner’s dilemma are similar to cooperation rates in the standard one-shot prisoner’s dilemma*

### C.2 Preferences and beliefs

Table 11 presents the relationship between a subject’s own ambiguity aversion and their beliefs regarding their opponent’s ambiguity aversion. Again, the sample is restricted to subjects who filled in the comprehension drop down menus correctly on the first attempt; 95 of the 206 subjects failed this test, with most of those subjects failing comprehension for the game that measured their beliefs. Table 12 presents the relationship between a subject’s own risk aversion and their beliefs regarding their opponent’s risk aversion. Only 35 subjects failed the comprehensions tests for the risk games, leaving a sample size of 171 subjects.

The most striking feature of tables 11 and 12 is the extremely strong relationship between the subject’s own preferences and their beliefs regarding their opponents preferences. On both the risk and ambiguity dimension the Fisher exact test rejects the null hypothesis that preferences and beliefs are independent at all reasonable significance levels.

The results in the main text suggest that subjects were not very confident in their predictions of their opponent’s preferences, while the results here demonstrate that subjects predicted their opponent to behave like themselves. A reconciliation of these facts is that when faced with predicting behaviour in an uncertain environment the subject’s own behaviour acts as a very strong focal point.

**Result 8.** *Subjects believe that their opponents preferences are the same as their own preferences.*

### C.3 Comprehension Data

This section provides an analysis of the comprehension data, and a discussion of the robustness of the results presented in the main body of the paper. Table 13 presents the subjects comprehension
Table 11: Subject’s own ambiguity preferences crossed with subject’s predictions of their counterpart’s ambiguity preferences, restricted to subjects who passed the comprehension test for the relevant games. Percentages are the cell count as a percentage of the row total. Non-directional Fisher’s exact test $p < 1 \times 10^{-10}$.

<table>
<thead>
<tr>
<th>Own ambiguity preference</th>
<th>Predicted ambiguity preference</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Neutral</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Averse</td>
<td>4 (6%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Neutral</td>
<td>63 (94%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Averse</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>32 (73%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>12 (27%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Neutral</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Own ambiguity preference</td>
<td>67</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Averse</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>44</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 12: Subject’s own risk aversion crossed with subject’s predictions of their counterpart’s risk aversion, restricted to subjects who passed the comprehension test for the relevant games. Percentages are the cell count as a percentage of the row total. Non-directional Fisher’s exact test $p < 1 \times 10^{-10}$.

<table>
<thead>
<tr>
<th>Own risk aversion</th>
<th>Predicted risk aversion</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Low</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>73 (74%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>6 (6%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>19 (19%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>98</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Med</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>5 (31%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>9 (56%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2 (13%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>16</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>High</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>9 (16%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2 (3%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>46 (81%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>57</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Low</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>87 (51%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>17 (10%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>67 (39%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>171</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

scores broken down by game number, and table 14 presents the aggregated data. As the tables demonstrate, only about a quarter of the subjects answered all of the comprehension questions correctly on their first attempt. Subjects performed better on the risk measurement game than the ambiguity measurement game, and also performed better as the row player (measuring their own preferences) than as the column player (measuring their beliefs regarding their opponent’s preferences) in these games. Performance on the ambiguous prisoner’s dilemma game was also quite poor.

There are obviously many different inclusion criteria that could be constructed using the comprehension data. The results in this paper were not data-mined by choosing the most convenient inclusion criteria. Ex-ante, two candidate inclusion criterion were identified. One was the criterion used in the paper. The other criterion was to only use subjects who score a perfect 7 out of 7 on the comprehension questions.

The latter criterion was unable to be used because of the small and unbalanced sample sizes that it produced. For example, of the 52 subjects who satisfied the criterion only 8 were risk neutral and ambiguity averse, while only 4 were risk averse and ambiguity neutral. Therefore, this criterion
<table>
<thead>
<tr>
<th>Comp Score</th>
<th>$2_R$</th>
<th>$2_C$</th>
<th>$5_R$</th>
<th>$5_C$</th>
<th>$6_R$</th>
<th>$6_C$</th>
<th>$9$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>159</td>
<td>131</td>
<td>196</td>
<td>177</td>
<td>168</td>
<td>179</td>
<td>139</td>
</tr>
<tr>
<td>0.75</td>
<td>26</td>
<td>39</td>
<td>5</td>
<td>18</td>
<td>32</td>
<td>21</td>
<td>44</td>
</tr>
<tr>
<td>0.5</td>
<td>7</td>
<td>13</td>
<td>2</td>
<td>5</td>
<td>2</td>
<td>4</td>
<td>7</td>
</tr>
<tr>
<td>0.25</td>
<td>9</td>
<td>4</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>3</td>
</tr>
<tr>
<td>0</td>
<td>5</td>
<td>19</td>
<td>3</td>
<td>5</td>
<td>3</td>
<td>2</td>
<td>13</td>
</tr>
<tr>
<td>Total</td>
<td>206</td>
<td>206</td>
<td>206</td>
<td>206</td>
<td>206</td>
<td>206</td>
<td>206</td>
</tr>
</tbody>
</table>

Table 13: Number of subjects attaining each comprehension scores for each of the seven games played. Subjects were awarded a comprehension score of 1 for answering the comprehension questions correctly on the first attempt, and were penalized 0.25 for each incorrect attempt. The column heading $2_R$ (resp. $2_C$) indicates the responses to the game in figure 2 as the row (resp. column) player.

<table>
<thead>
<tr>
<th>Total Comp Score</th>
<th>Number of Subjects</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>52</td>
</tr>
<tr>
<td>6.75</td>
<td>59</td>
</tr>
<tr>
<td>6.5</td>
<td>35</td>
</tr>
<tr>
<td>6.25</td>
<td>12</td>
</tr>
<tr>
<td>6</td>
<td>15</td>
</tr>
<tr>
<td>5.75</td>
<td>8</td>
</tr>
<tr>
<td>5.5</td>
<td>6</td>
</tr>
<tr>
<td>5.25</td>
<td>2</td>
</tr>
<tr>
<td>5</td>
<td>3</td>
</tr>
<tr>
<td>4.75</td>
<td>5</td>
</tr>
<tr>
<td>4.5</td>
<td>1</td>
</tr>
<tr>
<td>4.25</td>
<td>1</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>3.75</td>
<td>1</td>
</tr>
<tr>
<td>3.5</td>
<td>2</td>
</tr>
<tr>
<td>3.25</td>
<td>1</td>
</tr>
<tr>
<td>1.25</td>
<td>2</td>
</tr>
<tr>
<td>Total</td>
<td>206</td>
</tr>
</tbody>
</table>

Table 14: Total comprehension score by subject. A score of 7 indicates that the subject answered the comprehension questions correctly on the first attempt for each of the 7 games.
was rejected for not providing enough power, and the criterion in the main text was adopted.

It is also useful to check some other potential inclusion criteria, ex-post, as a robustness analysis. The results on preferences (result 1) are robust across different criteria, which is not surprising given how strong they are. Result 2, regarding the joint explanatory power of risk and ambiguity preferences, is also robust. The negative results regarding the ability of beliefs to explain behaviour are also robust.

Result 4, regarding the explanatory power of ambiguity aversion after controlling for risk aversion, is fragile as the inclusion criteria changes. The unconditional explanatory power of ambiguity aversion (presented in the appendix) is more robust. This provides another potential explanation for the lack of correlation between behaviour in the games and Ellsberg tasks in Kelsey and le Roux (2015a); because they had no comprehension tests, they have a noisier sample than the one presented in the main text here.

D Instructions

The instructions presented to subjects in the September sessions subjects are reproduced below. The instructions in the March and April sessions had a different example game presented as “Game X”. Otherwise, the two sets of instructions were identical. The instructions were originally written in html and css and were presented to students on their computer in an Internet browser. The instructions were interactive, and subjects could highlight strategies in the example games and practice filling in the drop down menus for “Game X”.
Instructions

This is a research experiment designed to understand how people make economic decisions. To assist with our research, we would greatly appreciate your full attention during the experiment. Please do not communicate with other participants in any way and please raise your hand if you have a question.

You will participate in a series of 7 games. In each game you will make one decision, and a subject will be paired with, called your counterpart, will make one decision. One, and only one of the games will be chosen, in a random fashion described below, as the game for which you will be paid. The amount that you earn will depend on a combination of your decision, your counterpart’s decision and, for some games, the colour of a ball drawn from a bag. Your counterpart will be one of the other participants in this room and the identity of your counterpart has been randomly pre-determined.

How your payment will be determined

As mentioned above, only one game will be chosen as the game for which you will be paid. Each of the 7 games is equally likely to be chosen. You will notice that there are 7 pieces of paper labelled from A to G stuck to the wall. On the back of each of them is a number. At this point, I would like to ask one of you to choose one of the pieces of paper labelled from A to G. The number that is written on the back of the chosen piece of paper will determine which of the 7 games is chosen for payment. Although the choice of game has already been fixed by the choice of letter, we will not reveal the choice to you until the end of the experiment. This procedure suggests that you should treat each game independently (i.e. as if it was the only game in the experiment). After the experiment you may come and check that each of the games actually is represented on the back of one of the cards.

Your payment may also depend on the colour of a ball drawn from a bag. In some games there will be no balls drawn, in some other games there will be only one ball drawn from a bag, and in some games there will be two balls drawn (each from a different bag). The ‘unknown’ bag (denoted by the letter U) will contain only RED and YELLOW balls in an unknown ratio, while the ‘known’ (denoted by the letter K) bag will contain RED and YELLOW balls in an equal ratio. The total number of balls in each bag will always be 10. A graphical representation of the two bags is shown below.

![U bag and K bag](image)

When you are playing the games there will be a picture of the relevant bag(s) on the screen to remind you of the composition of the bag(s).

Before the experiment begun, I asked a graduate student in economics, who has no knowledge of this experiment, to place 10 balls into the U bag. I instructed the student to place exactly 10 balls in the bag, and that only RED and YELLOW balls are to be placed in the bag. I have no knowledge of the composition of the balls in the bag, other than what is described above. There might be 10 RED balls and 0 YELLOW balls, or 9 RED balls and 1 YELLOW ball, or 8 RED balls and 2 YELLOW balls, and so on up to 0 RED balls and 10 YELLOW balls. After the experiment you may come and check that the bag satisfies the requirements outlined above.

I shall now create the K bag, by placing 5 RED balls and 5 YELLOW balls into a second bag.

At the end of the experiment, after the chosen game has been revealed, I will ask one of you to draw a ball from the K bag (if required), and another one of you to draw a ball from the U bag (if required).

The combination of the game chosen, your choices, your counterpart’s choices and the colour of the ball(s) will determine how much money you make during the experiment. The amount that you make during the experiment will be added to your $5 show up fee and will be paid to you, in cash, at the end of the experiment.

One of the conditions of the ethics approval for this experiment is that I do not deceive the subjects (i.e. you). If you feel that I have deceived you in any way, you may contact either my thesis supervisor or the UBC Behavioural Ethics Review Board to lodge a complaint. Their contact details are included on the consent form that you have read and signed.

The structure of the games

In each game, you will need to make a choice of either A or B or C (in some games you will only have 2 options, A and B). You may only ever choose one option per game. Your counterpart will make a choice of either X or Y or Z (in some games your counterpart will only have Z options, X and Y). Your counterpart may also only ever choose one option per game. The amounts that each of you can earn will be presented to you in a table format, as seen below.

<table>
<thead>
<tr>
<th>Counterpart’s Choices</th>
<th>X</th>
<th>Y</th>
<th>Z</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>20, 10</td>
<td>8, 0</td>
<td>0, 0</td>
</tr>
<tr>
<td>B</td>
<td>30, 0</td>
<td>6, 10</td>
<td>4, 0</td>
</tr>
</tbody>
</table>
Your options will always be shown on the rows of the table. Your counterpart's options will always be shown on the columns of the table (the computer flips the game so that everyone can look at the table from the same perspective). Within each cell of the table your earnings will always be shown first, in bold, and your counterpart's earnings will always be shown second. Values shown are always shown dollar amounts. For example, in the above game, if you chose action 'A' and your counterpart chose action 'Y' then you would receive a $8 and your counterpart would receive $0. On the other hand, if you chose 'A' and your counterpart chose 'Z' then you would each earn $0. Games that have only a single payoff table, like the above example, do not require a ball to be drawn.

In other games, your earnings will also depend on the colour of a ball which will be drawn from a bag after you have both made your decisions. These games will have two tables, and the colour of the ball(s) will determine which table is used to calculate your earnings. In the example given below, the left table will be used if a RED ball is drawn and the right table will be used if a YELLOW ball is drawn.

Suppose, in the above example, that you chose option 'B' and your counterpart chose option 'Y'. Then your payment will be $9 if the ball drawn is RED, and $4 if the ball drawn is YELLOW. Your counterpart's payment will be $10 if the ball drawn is RED, and $10 if the ball drawn is YELLOW.

The game shown above was a K game. In a K game there is only one ball drawn, from the K bag, and the colour of the ball will determine which table will be used. There will also be U games, where there is also only one ball drawn, from the U bag. The other type of game, a U and K game, is shown below. It will always be clear which type of game you are playing from the labels on the tables and the pictures of the bags underneath the game.
In a U and K game there will be two balls drawn - one from each of the bags. If a RED ball is drawn from the U bag then you will be paid according to the left hand table. If a RED ball is drawn from the K bag then you will be paid according to the right hand table. It is also possible that a RED ball will be drawn from both bags. In this case, you would be paid according to both tables (the payments will be added together). However, it is also possible that a RED ball will not be drawn from either bag. In this case you would receive no payment (other than the $5 show up fee and any bonus payments you may earn).

**Bonus payments and drop down menus**

Before you can confirm your choices in the game itself, you will need to fill in a series of dynamic drop down menus to confirm that you have understood the game. You should pay careful attention to the drop down menus, because you will earn bonus payments that depend on whether you have filled the drop down menus correctly.

For each game, you should fill in the drop down menus first. Once you are happy that your choices adequately describe the game, you should click on the "Check Description" button. If you fill in the drop down menus correctly on your first attempt you will earn a $1 bonus for that game. As there are 7 games, you may earn up to $7 in bonus payments. If you click 'Check Description', but have filled in the dropdown menus incorrectly or have not filled the dropdown menus in all, your bonus payment will decrease by $0.25. After four incorrect attempts your bonus payment for only that game will reach zero.

**WARNING:** The bonus payment system relies on 'alerts' that will pop up on your screen. Sometimes the Chrome browser will give you option of turning the alerts off. Do not do this; if you do then the computer may not record your bonus payments. If you accidentally turn the alerts off then please raise your hand and we will reset your browser.

Before we continue shall work through an example of the drop down menus together.

**Game Number X**

<table>
<thead>
<tr>
<th>Counterpart's Choices</th>
</tr>
</thead>
<tbody>
<tr>
<td>X</td>
</tr>
<tr>
<td>A</td>
</tr>
<tr>
<td>B</td>
</tr>
<tr>
<td>C</td>
</tr>
</tbody>
</table>

**RED ball drawn from K bag**

<table>
<thead>
<tr>
<th>Counterpart's Choices</th>
</tr>
</thead>
<tbody>
<tr>
<td>X</td>
</tr>
<tr>
<td>A</td>
</tr>
<tr>
<td>B</td>
</tr>
<tr>
<td>C</td>
</tr>
</tbody>
</table>

**YELLOW ball drawn from K bag**

**Choice A:** Your earnings for this choice affected by your counterparts’ strategy.

**Choice B:** Your earnings for this choice affected by your counterparts’ strategy.

**Choice C:** Your earnings for this choice affected by your counterparts’ strategy.

You may type whatever you want here. This textbox may be enlarged by dragging the lower right corner.

Note that most of the games appear in pairs - each game has two players, and you will play each game in each role. (Recall that there are seven games - the seventh game does not have a pair). Below is an example of Game X (with the drop down menus removed), viewed from the other role. Notice that while in Game X your earnings were not affected by your counterpart's choices, in Game XT your counterpart's earnings are not affected by your choices.

**Game Number XT**
How to use the game interface

Once your description of the game is correct (and you have verified this by clicking the "check description" button) the drop down menus will inactivate, and the "lock" button will activate. At this point you can enter your choice by clicking on the desired option in the table. When you click on a choice, the computer will highlight the row that you have chosen (you may try this in Game X above). If you want to change your mind, you can simply click on a different choice. Once you are happy with your choice you should click on the "lock" button before moving on to the next game. If, later, you wish to change your mind you can always click on the "unlock" button and then change your choice.

You may also highlight any of your counterpart’s options by clicking on the label for that choice (as long as the game is unlocked) - this feature is provided to you as a visual aid to assist in your decision making process, but will have no impact on the earnings received by either you or your counterpart. There is another decision making aid that has been provided to you: a textbox. In the past, some subjects have found it useful to write down the reasoning behind their decisions. You do not have to write anything in the textbox, and nothing you do write in the textbox will be used in the determination of your earnings. Nothing you write will be shown to your counterpart. Likewise, nothing your counterpart writes will be shown to you. When you lock a game, the textbox associated with that game will lock as well.

Once you have entered your choices for each of the 7 games, and locked each of the 7 games, you can click the button to submit all of your answers. Once you have pressed the "submit" button you can no longer go back and change your answers. Once everyone has clicked submit, the computer will match your responses with your counterpart's choices. The computer will not match you with your counterpart until everyone has finished the experiment, so there is no advantage to rushing. Take your time and make sure you are happy with your choices.

Summary of the order of events

1. Read instructions, and choose a letter on the wall that will determine which game will be paid.
2. Play the 7 games. For each game, begin by filling in the drop down menus, and then make your choice in the game. Lock each game after you have made your choice. If you want to change your mind, you can always unlock any game and change your choice.
3. Once you are happy with all of your choices, press the 'submit' button. Once you have pressed the 'submit' button your choices are final.
4. Enter some demographic information into the computer.
5. Reveal the game that will be paid.
6. Draw ball(s) from the bag(s).
7. Calculate your payment, based on the chosen game, colour of ball, your action and your counterpart’s action.
8. Receive payment and leave the experiment.