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Philipp Külpmann and Davit Khantadze

Center for Mathematical Economics (IMW)
Bielefeld University
Universitätsstraße 25
D-33615 Bielefeld · Germany

e-mail: imw@uni-bielefeld.de
http://www.imw.uni-bielefeld.de/wp/
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Identifying the reasons for coordination failure in a laboratory experiment*

Philipp Külpmann[†] Davit Khantadze[‡]

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Abstract

We investigate the effect of absence of common knowledge on the outcomes of coordination games in a laboratory experiment. Using cognitive types, we can explain coordination failure in pure coordination games while differentiating between coordination failure due to first- and higher-order beliefs.
In our experiment, around 76% of the subjects have chosen the payoff-dominant equilibrium strategy despite the absence of common knowledge. However, 9% of the players had first-order beliefs that lead to coordination failure and another 9% exhibited coordination failure due to higher-order beliefs. Furthermore, we compare our results with predictions of commonly used models of higher-order beliefs.

JEL codes: C72, C92, D83
Keywords: Higher-order beliefs, coordination failure, cognitive abilities, experimental economics, game theory

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[†]Bielefeld University, `philipp.kuelpmann@uni-bielefeld.de`
[‡]University of Warwick, `d.khantadze@warwick.ac.uk`

1. Introduction

If you have lost your spouse in a department store and both of you are trying to find each other, the answer to the (seemingly simple) question of "Will she look for me at the coffee bar or at the exit?" depends not only on the answer to the question "Does she think I am looking for her at the coffee bar or at the exit?" (i.e., something we will call the first-order belief) but also on the answers to "Does she think that I think that she thinks that I am looking for her at the coffee bar or at the exit?" (i.e., the second-order belief or "What is her first-order belief?") and on infinitely more levels of beliefs. This paper addresses the question if people actually use beliefs of a higher order.

When modeling human behavior, most works assume that players have common knowledge about the structure of the game, i.e., that all players know the structure, that all players know that everyone else knows the structure and so on.[1] Furthermore, we assume that players do not only have common knowledge about publicly known properties of the game but also about the distributions of unknown factors of the game, like the other players' types (for example if I'd rather wait at the coffee bar or the exit). The absence of common knowledge leads to complex belief hierarchies, so called *higher-order beliefs*. The first level of these beliefs, so called first-order beliefs, might be a belief over the other player's type. A second-order belief would then be a belief over the belief of the other player about your type (i.e., a belief over the other player's first-order belief) and so on ad infinitum.

In the game theoretical literature many different assumptions and models of higher-order beliefs exist and many of these lead to very different predictions even in simple games like the pure coordination game we are using in this paper.[2] The question, what kind of model of higher-order beliefs players actually use, seems to be an empirical question which we are trying to address in this paper.

To do so, we take up the experimental results and setup of Blume and Gneezy (2010), in which there is an issue of cognitive difficulties, to analyze the effects of higher-order beliefs. Blume and Gneezy (2010) were able to show that participants form beliefs about the cognitive abilities of other participants and, if these beliefs are pessimistic, they hinder coordination between the players (i.e., that "beliefs matter"). However, they have not taken into account the effect of higher-order beliefs about cognitive abilities. Therefore, we modify their experimental setup in

[1] However, there is a (mostly theoretical) literature on universal type spaces, introduced by Harsanyi (1967/68) and formalized by Mertens and Zamir (1985) and Brandenburger and Dekel (1993), analysis games without common knowledge.

[2] A brief overview of some models of higher-order beliefs can be found in Section 1.1 and a more detailed discussion in Appendix B.

order to distinguish the effect of first-order beliefs players form about the cognitive ability of their opponents (i.e., if players trust in the cognitive ability of their partners) and higher-order beliefs.

We introduce a new treatment in which participants guess what other participants play against themselves. This allows us to identify first-order beliefs and therefore separate first- from higher-order beliefs.

Using the data from these treatments, we can answer the following three questions:

- **Are players able to coordinate in the absence of common knowledge?**
- Can coordination fail because players underestimate the skill of the other players? Or, in other words, **do first-order beliefs matter?**
- Can coordination fail because players think ”too much“ about what others might think? Or, in other words, **do higher-order beliefs matter?**

Using Blume and Gneezy's (2000) 5-sector disc, we were able to find answers to all three questions: In the experiment, we were able to reproduce Blume and Gneezy's (2010) result, that the majority of players had no problem choosing the Pareto-dominant equilibrium strategy of the game (i.e., coordination is possible). Furthermore, some players switch to the worse equilibrium strategy because of first- and higher-order beliefs (i.e. first- and higher-order beliefs matter).

More important applications than the search for ones husband or wife in a department store are suggested by recent studies in sociology and development studies, like Bicchieri (2005) suggest that common knowledge plays a significant role in the fight against female genital mutilation. Our results might help to improve our understanding of why some organizations are significantly more successful in the fight against female genital mutilation than others.

The paper is organized as follows: In Section 1.1, we will give an overview of the relevant literature and how our work fits into it. Then we will explain an example of the game we use in Section 2. In Section 3 we will explain the model. This is followed by the experimental design in Section 4 and the results of the experiment in Section 5. The aforementioned application to the fight against female genital mutilation is discussed in Section 6. Finally, we will conclude in Section 7.

1.1. Related works

There is a large theoretical literature, beginning with the seminal paper on the "email game" by Rubinstein (1989), showing that higher-order beliefs play a role in determining the outcome of a game. For instance, Carlsson and Van Damme (1993) use higher-order beliefs (in their model of global games) to identify the risk-dominant equilibrium as the unique rationalizable outcome of the coordination game. This uniqueness result spawned a large applied literature on, among other areas, bank runs and arms races, in e.g. Morris and Shin (1998), Morris and Shin (2004), Baliga and Sjöström (2004), Corsetti, Dasgupta, Morris, and Shin (2004), and Goldstein and Pauzner (2005). Weinstein and Yildiz (2007b), however, have shown that this uniqueness result, that this whole literature depends on, is fragile to the exact specification of the higher-order belief model. Other "nearby" higher-order belief models have very different "unique" predictions. In fact, they show that any rationalizable outcome of the original game, can be obtained as the unique rationalizable strategy profile of some higher-order belief model.

Weinstein and Yildiz (2007a) establish a condition, called "global stability under uncertainty". This condition implies that, if the change in equilibrium actions is small in the change of kth-order beliefs and higher, equilibria can be approximated by the equilibrium with at most kth-order beliefs. Unfortunately, pure coordination games do not fulfill "global stability under uncertainty".

Strzalecki (2014) and Kneeland (2016) develop different non-equilibrium approaches, inspired by the experimental literature discussed later, using bounded levels of reasoning to explain behavior in coordinated attack problems (e.g. Rubinstein's (1989) email game).
A more in-depth discussion of models of higher-order beliefs and their predictions of the results of our experiment can be found in Appendix B.

The experimental literature, however, has so far mostly focused on strategic uncertainty. The most prominent example for this is probably the literature on level-k thinking or cognitive hierarchy models, which was started by Nagel (1995) and Stahl and Wilson (1995). In recent years, there have been many studies conducted, using and analyzing level-k reasoning, for example Ho, Camerer, and Weigelt (1998), Costa-Gomes, Crawford, and Broseta (2001), Camerer, Ho, and Chong (2004) and Crawford, Gneezy, and Rottenstreich (2008). For a recent survey, see Crawford, Costa-Gomes, and Iriberri (2013).

But there also have been works which do not focus on strategic uncertainty. For example Heinemann, Nagel, and Ockenfels (2004), Cornand (2006), Cabrales, Nagel, and Armenter (2007) and Duffy and Ochs (2012) who directly test implications of the theory of global games, i.e. individuals play an incomplete information game as in Carlsson and Van Damme (1993). The results however, are mixed and range from full support to full rejection of the predictions made by global games.

Another, closely related work is Kneeland (2015), in which she explores the level of rationality, a requirement for higher-order beliefs, of players experimentally. She shows that, in her experiment, 94% of all players are rational with decreasing numbers for second- (71%), third- (44%) and forth-order (22%) rationality.

We explore experimentally the "depth of reasoning" individuals employ when playing slightly difficult coordination games. In fact we want to abstract away from purely strategic concerns by only looking at coordination games in which the incentives of the players are perfectly aligned and a Pareto-dominant equilibrium exists. The fundamental uncertainty in the model will be one about the cognitive abilities of the opponents.

Differences in cognitive abilities have been studied before, for example by Gill and Prowse (2016), who have shown that more cognitively able subjects converge, in repeated p-beauty contests, more frequently to equilibrium play and earn more. Furthermore, Proto, Rustichini, and Sofianos (2014) have shown that intelligence affects the results of repeatedly played prisoner's dilemmas, in which groups of higher intelligence tend to cooperate more frequently in later stages of the game. Agranov, Potamites, Schotter, and Tergiman (2012) have shown, by manipulating the perception of the cognitive levels of other players, that beliefs about the level of reasoning do play a significant role in the presence of strategic uncertainty. Alaoui and Penta (2015) establish a framework in which the depth of reasoning is endogenously determined by different cognitive costs of reasoning.

The way we model cognitive differences however, builds on another branch of literature. Motivated by Schelling's (1960) discussion of focal points, a variety of authors have tried to formally capture his ideas, most notably Bacharach (1993) and Sugden (1995). The importance of focal points is supported by many experiments, for example by Mehta, Starmer, and Sugden (1994), who have replicated Schelling's results and have shown that coordinating on a focal point is different from accidental coordination. Crawford, Gneezy, and Rottenstreich (2008) have shown that, in a pure coordination game with symmetric payoffs, salient labels lead to a high percentage of coordination whereas even slight asymmetries in payoffs might lead to a coordination failure. Isoni, Poulsen, Sugden, and Tsutsui (2013) extend the analysis to bargaining problems and show that payoff-irrelevant clues help to improve coordination, even if there is no efficient or equal division.

In the absence of clues however, the theory of focal points can not be applied. Formally the absence of clues can be modeled as symmetries between strategies and players in a given game. In fact Nash (1951) has already discussed equilibrium under symmetry restrictions (and shown existence also of such symmetric (mixed) equilibria for finite games). Crawford and Haller (1990) have defined symmetries in games and used these definitions to see what focal points in highly symmetric repeated coordination games would look like.[3] Blume (2000) has further developed this symmetry concept to talk about play under the absence of a

[3] Bhaskar (2000) and more comprehensively Kuzmics, Palfrey, and Rogers (2014), have studied theoretically and in the latter case also experimentally, what the possible focal points of the symmetric repeated battle-of-the-sexes and its generalizations could be.

common language. Other notions of symmetries have been put forward and studied in Harsanyi and Selten (1988), Casajus (2000) and Casajus (2001). Alós-Ferrer and Kuzmics (2013) have then clarified the difference between different notions of symmetries and characterized all the possible ways a frame (the way a game is presented to players in the lab, for instance) could lead to different symmetry restrictions (and therefore to different focal points).

All these models of symmetries and restrictions are implicitly or explicitly investigated under the assumption of perfectly rational individuals. However, identifying all symmetries (and especially non-symmetries) in a game can be a difficult task. Bacharach (1993) has proposed his variable frame theory to allow for individual players with different states of mind or, as developed by Blume (2000) and employed by Blume and Gneezy (2000) and Blume and Gneezy (2010), with different cognitive abilities.

This finally brings us to the goal of our study. We want to take up the experimental results and setup of Blume and Gneezy (2010) to analyze the effects of higher-order beliefs. They were able to show that participants form beliefs about the cognitive abilities of other participants and, if these beliefs are pessimistic, they hinder coordination between the players. However, they have not taken into account the effect of higher-order beliefs about cognitive abilities. Therefore, we modify their experimental setup in order to distinguish the effect of first-order beliefs players form about the cognitive ability of their opponents and higher-order beliefs.

2. Example

In this example, players only have access to two strategies l and h and are trying to coordinate on one of them; the payoffs are as depicted in the payoff matrix in Figure 1. As (h, h) has a higher equilibrium payment it would therefore be the focal point (and the risk- and payoff-dominant Nash equilibrium) of this particular game.[4]

	l	h
l	1,1	0,0
h	0,0	3,3

Figure 1: Payoff matrix of a high-cognition player

However, if we introduce cognitive differences, i.e., if action h is only available

[4]Or, in the words of Luce and Raiffa (1957) and Schelling (1960) a *solution in the strict sense*.

to a high-cognition player and low-cognition players are not aware of the existence of action h (and the high type) and are therefore forced to play l, beliefs about the other player's type might lead to coordination failure,[5] even if both players are high-cognition players. The driving force of this result is the absence of common knowledge about the players' type or the fraction of high cognition players.

This game models the situation in which one player is not aware that there even is an action to take (i.e., they don't have complete knowledge about the structure of the game).

The following two examples show how beliefs could lead to coordination failure between two high-cognition players: First imagine that the first player (she) thinks that the other player (he) is a low-cognition player. Then she would play l, as he would have no other choice than playing l. This is what we will call coordination failure due to a first-order belief. The second example is that she thinks that his type is high, he thinks she is a high-type player but she thinks that he thinks her type is low. Again, she would play l as she thinks that he will play l. Here we have a coordination problem due to her second-order belief. Therefore, even if both players have the ability to coordinate on the best equilibrium, they might end up failing to coordinate on the better equilibrium (h, h).

The existence of infinitely many levels of beliefs and that a "bad" belief at any level makes the player switch to the "bad" strategy l makes one wonder, if, even with a high fraction of high-cognition players, coordination on the good equilibrium (h, h) is possible.

Therefore, the first main question this paper addresses is if coordination on the good equilibrium can be expected even in the absence of common knowledge. The second question is if systematic underestimation of other players' skills can be a source of coordination failure, or if first-order beliefs matter. The third and last question is if higher-order beliefs, e.g. if she thinks that he thinks that she is a low type, are a possible cause for coordination failure or if these levels of reasoning are too complex and play no significant role in coordination games.

The concepts of coordination games and higher-order beliefs will be formalized in the following section and the experimental design will be explained in Section 4.

3. The model

We begin by defining a pure coordination game for two players.

[5] In this paper, we follow the notion for coordination failure of Van Huyck, Battalio, and Beil (1990), i.e., the failure to coordinate on the best achievable outcome. That means, even if two high-cognition players coordinate on a Pareto-inferior equilibrium we will call it coordination failure.

Definition 1 (Pure coordination game)**.** A *pure coordination game* is a game with 2 players, who each have access to m different actions ($\{a_1, a_2, \ldots, a_m\}$).
In this game payoffs of a player i are defined as

$$u_i(a_i, a_j) = \begin{cases} x_i & \forall i, j : i = j \\ 0 & \text{otherwise} \end{cases}$$

with $x_m > x_{m-1} > \cdots > x_1$.

This means that each player can choose from the same set of actions and whenever they have picked the same action they get the same payoff and if they don't manage to coordinate their actions, both get nothing. Furthermore, there is a Pareto ordering of these equilibria. Figure 2 shows an example of a pure coordination game with three possible actions.

	a_1	a_2	a_3
a_1	1, 1	0,0	0,0
a_2	0,0	2, 2	0,0
a_3	0,0	0,0	4, 4

Figure 2: A pure coordination game

Let us now introduce cognitive differences into this pure coordination game. For the sake of simplicity, we are only introducing two cognitive types, a low-cognitive type and a high-cognitive type. The latter has access to a "better" strategy, which is not available to the low type. Furthermore, the low type is unaware of the existence of the high type, as proposed by Bacharach (1993).

This means that the low type has no complete knowledge about the structure of the game and therefore common knowledge about it is, as long as there is at least one low cognition player, not possible.

Definition 2 (Pure coordination game with cognitive differences)**.** A *pure coordination game with cognitive differences* is a game with 2 players. Each of the players has a type $t_i \in \{low, high\}$ and has access to different strategies, depending on his type t_i. The types of a player are her private information. Low cognition players have access to $\{a_1, a_2, \ldots, a_{m-1}\}$ whereas high cognition players also have access to the action a_m, i.e. to $\{a_1, a_2, \ldots, a_m\}$. Furthermore, low cognition players have no knowledge about the existence of the high type or action a_m.
In this game payoffs of a player i are defined as

$$u_i(a_i, a_j) = \begin{cases} x_i & \forall i, j : i = j \\ 0 & \text{otherwise} \end{cases}$$

with $x_m > x_{m-1} \geq \cdots \geq x_1$.

These cognitive differences can also be thought of as symmetry constraints on attainable strategies, as proposed by Crawford and Haller (1990) and further developed by Blume (2000) and Alós-Ferrer and Kuzmics (2013). Here, the high-cognition player has less symmetry constrains and has therefore more attainable strategies.

In the experiment we are using the notion of cognitive differences as proposed by Blume and Gneezy (2010) (a generalization of Bacharach's variable frame theory, using different symmetry constraints on the attainable strategies as used in Blume (2000)).

For a formal description of the belief hierarchy of these games, we would like to refer to Appendix A. However, we believe for understanding the results of this work, the idea conveyed in this section should suffice.

4. Experimental design

Measuring higher-order beliefs is very complicated, as there is an "uncertainty principle" (as already discussed by Blume and Gneezy (2010)) at work; i.e., it is hard to measure beliefs without introducing or changing them.[6] Furthermore, introducing absence of common knowledge is difficult; When told that they are given a random number, subjects usually assume that it is drawn from a uniform distribution. Explicitly stating that the distribution is unknown leads to a myriad of other problems. Subjects could for example assume a strategic selection of the distribution by the experimenter. Finally, we need to have some sort of control over the fraction of high-cognition players, so that the action only available to the high-cognition players is the one with the highest expected payoff (see Appendix B).

We solve all three problems by utilizing Blume and Gneezy's (2000) 5-sector disc. This is a disc with 5 equally large sectors on it, 2 black and 3 white, as depicted in Figure 3.[7]

The disc has the same sectors on the front- and backside of the disc and can be flipped and rotated.

[6] Either by making the subjects realize that there might be something like a higher-order belief or by them trying to be a good subject (Orne (1962)). A more extensive discussion of this uncertainty principle can be found in Appendix C.

[7] There is a second version of this disc, with a significantly harder to find distinct sector, with adjacent black sectors. However, for this disc, the fraction of players who were able to identify the distinct sector is too small (i.e., not satisfying the conditions derived in Appendix B). Some choice data from this "hard disc" can be found in the Online Appendix.

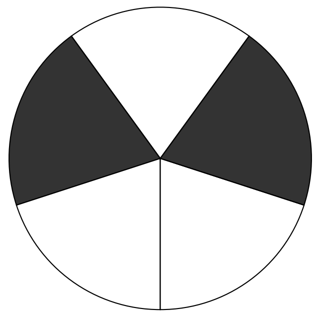

Figure 3: 5-sector-disc

As the disc can be flipped, the subjects face symmetry constraints and can therefore not distinguish all five sectors. These symmetries cannot be overcome and therefore not all Nash equilibria are possible given the particular frame. Only certain "attainable" equilibria are possible, as defined originally in Crawford and Haller (1990), and further developed by Blume (2000) and Alós-Ferrer and Kuzmics (2013).

The property of this disc which is most important for this paper is that it has a single distinct white sector: The sector adjacent to both black sectors (Figure 3).[8]

For the subjects there are then, in principle, three distinguishable sets of sectors: the black sectors (B), the uniquely identifiable white sector (D), and the other white sectors (W').

The key assumption behind the experiment (and also behind Blume and Gneezy (2000) and Blume and Gneezy (2010) and very much supported by their findings), is that not all subjects realize that there is a uniquely identifiable sector, which leads to two different cognitive types, the high type, who can identify the distinct sector, and the low type, who cannot.

The low type then faces an additional symmetry constraint and has only two distinguishable sets of sectors to choose from: One of the two black sectors (B) or one of the three white sectors (W).

Note that the lower type has no knowledge about the existence of another type or the distinct sector.

The subjects then played three treatments in a random order without feedback after hearing and reading the instructions and completing an extensive quiz:[9]
The **Self Treatment** in which the subject gets the disc twice, every time randomly turned and rotated, and gets £5 if she picks the same sector twice.
In the **Prediction Treatment** one subject (she) is told that another subject (he) plays the *Self Treatment* (with a possibly differently turned and rotated disc). She has to

[8]More about the properties of this disc can be found in Blume and Gneezy (2000).
[9]For the complete instructions and a description of the quiz see the Online Appendix.

pick one sector and every time he picks the sector she picked, she gets £2.5.[10] Finally, the **Coordination Treatment**, in which two players pick simultaneously a sector on a (randomly turned and rotated) disc and, if both players pick the same sector, both receive £5.

4.1. Predictions

How can we use this design to test the three initial questions stated in the introduction? Let us have a look how we expect low- and high-cognition players to behave in the three different treatments.

In the Self Treatment a high-cognition player has 9 possible choices: She can pick any of three actions (D, B, W') in the first stage and then pick any of the three actions in the second stage. This decision problem for the high-cognition player has a unique optimal solution: pick the distinct sector twice, giving her a probability to win of 1.

A low-cognition player is only aware of four possible choices: He can pick B or W in the first stage and then pick B or W in the second stage. The low-cognition player also has a unique optimal choice: pick B in both stages, giving him a probability to win of $\frac{1}{2}$.

Therefore, we would expect a high-cognition player to choose the distinct sector twice and a low-cognition player to pick a black sector twice.

In the Prediction Treatment, the action taken by a subject should only depend on her type and her first-order belief about the type of the other player. A low-cognition player will always choose B, whereas a risk-neutral, high-cognition player should pick D if his belief that the other player is also of the high type is at least $\frac{1}{3}$ and B otherwise.[11]

The coordination treatment is best depicted as a bi-matrix game with three (for the high-cognition player) and two (for the low-cognition player) pure strategies, with winning probabilities as depicted in Figure 4 and Figure 5. We expect a low-cognition player to play B, as it is the payoff- and risk-dominant equilibrium, whereas a high-cognition player's choice depends on her belief hierarchy: If anywhere in her complete hierarchy a belief lower than $\frac{1}{3}$ (or $\frac{1}{2}$ for very risk averse players) that the other player is a high-cognition player or that the other player thinks that she is a high-cognition player, . . . (or, in short, that there is no

[10] Adding another treatment in which subjects have to predict what another subjects does in the Prediction Treatment would, in theory, allow to explicitly check for second-order beliefs (or, when repeating this any higher-order belief). However, don't belief this will work with the 5-sector disc, as it probably requires too much attention and mental effort which most subjects might not be willing to exert.

[11] Allowing for risk-averse players, this fraction has to be between $\frac{1}{3}$ and $\frac{1}{2}$, depending on the degree of risk aversion.

common-p belief of $\frac{1}{3}$ or higher, that both players are high-cognition players), she will choose B, otherwise she will choose D.

	W'	B	D
W'	$\frac{1}{2}$	0	0
B	0	$\frac{1}{2}$	0
D	0	0	1

Figure 4: High-cognition player winning probabilities

	W	B
W	$\frac{1}{3}$	0
B	0	$\frac{1}{2}$

Figure 5: Low-cognition player winning probabilities

Unfortunately, neither the theoretical nor the experimental literature on higher-order beliefs can tell us which of the two will be chosen. Even small variations in the theoretical models of higher-order beliefs can generate both equilibria. More about models of higher-order beliefs can be found in Appendix B.

4.2. Hypotheses

Using our design, we can formulate three hypotheses to test the three research questions stated earlier. In the following we will use a shorthand for players' strategies such as: "W'W' B D" means that a player selected one of the two white sectors twice in the Self Treatment, one of the black sectors in the Prediction Treatment and the distinct sector in the Coordination Treatment.

The answer to our first question ″Is coordination possible? “ or, in the words of our model ″Do high-cognition players use the first-best strategy a_m despite the absence of common knowledge? “ is suggested by the literature on focal points (e.g., Sugden (1995) or Crawford, Gneezy, and Rottenstreich (2008)) and supported by the experimental literature on coordination games (e.g., Van Huyck, Battalio, and Beil (1990) or Cooper, DeJong, Forsythe, and Ross (1990)):

Hypothesis 1 (Coordination is possible)**.** *High-cognition players choose in the Coordination Treatment D more often than any other choice.*

We are using a within-subject design to test the hypotheses: Only high-cognition players can identify the best equilibrium, so we don't have to consider other types. We can identify these players with the help of the the Self Treatment. If high-cognition players, i.e., the ones who have been able to identify "D" in the Self Treatment, coordinate on D in the Coordination Treatment we know that coordination is possible, even in the absence of common knowledge.

The next two hypotheses extend on Blume and Gneezy's (2010) hypothesis that "beliefs matter": Hypothesis 2 formalizes the question "Does coordination fail because some high-cognition players underestimate the fraction of high-cognition players? " or "Is there coordination failure due to first-order beliefs? "

Hypothesis 2 (First-order beliefs matter)**.** *There are high-cognition subjects who choose a black sector in the Prediction Treatment and Cooperation Treatment, i.e., play "DD B B".*

We already know that we can identify players' types with the help of the Self Treatment. Furthermore, the Prediction Treatment identifies players who think that more than $\frac{1}{3}$ of the other players can not identify the distinct sector.

However, most of the problems in models of higher-order beliefs stem from the fact that there are infinitely many levels of beliefs. However, evidence from the laboratory indicates that people are not able to use higher-order rationality,[12] a requirement for coordination problems due to higher-order beliefs. Furthermore, even in studies of level-k reasoning, where players are framed and incentivized on using higher-order beliefs, players still rarely use high levels of reasoning.[13]

Therefore, the third question if there is is coordination failure due to higher-order beliefs, or if high-cognition players use the first-best strategy a_m despite the absence of common knowledge, arises naturally:

Hypothesis 3 (Higher-order beliefs matter)**.** *There are high-cognition subjects who play the distinct sector in the Prediction Treatment and a black sector in the Cooperation Treatment, i.e., play "DD D B".*

Our design allows for another robustness check: There is an attainable strategy which is very similar to the one we use to identify first- and higher-order beliefs: "DD B D". This strategy will only be chosen if players belief that their partner is of the low type, but still plays "D" in the in the Coordination Treatment. This strategy can therefore not be explained using our model.

Hypothesis (Robustness check)**.** *"DD B D" is played less often than "DD B B" and "DD D B".*

5. Results

The experiment was conducted at the DR@W Laboratory at the University of Warwick using the experimental software "z-Tree" developed by Fischbacher (2007). 130 subjects where recruited and received payments between £3 and £18. Before showing the results, let us briefly discuss the preliminaries of the experiment design.

[12]Kneeland (2015) shows that only about 22% of all players use more than third-order rationality.

[13]In Arad and Rubinstein's (2012) 11-20 game, 80 % of the players only use 3rd-order beliefs or lower despite the game being designed to facilitate higher-order reasoning.

The first preliminary is the focality of the distinct and the two black sectors. From the choice data in Figure 6 we can see that more than 95% of all players have chosen one of these sectors in the Coordination Treatment. The second preliminary is that there are enough high-cognition players, so that playing the high-cognition exclusive action is a payoff-dominant equilibrium for the players. In Figure 7 we can see that 58% of all players have chosen the distinct sector and are therefore considered high-cognition players. Therefore, playing the distinct sector would maximize the expected utility of high-cognition players in a game where the type distribution is common knowledge among high types independently of the degree of risk aversion (see Appendix B). We can also see that the second most frequently observed behavior is choosing a black sector twice, whereas choosing a white sector twice (which includes choosing the distinct white sector once and another white sector once) and picking one black and one white sector (labeled "Other") was very rare.

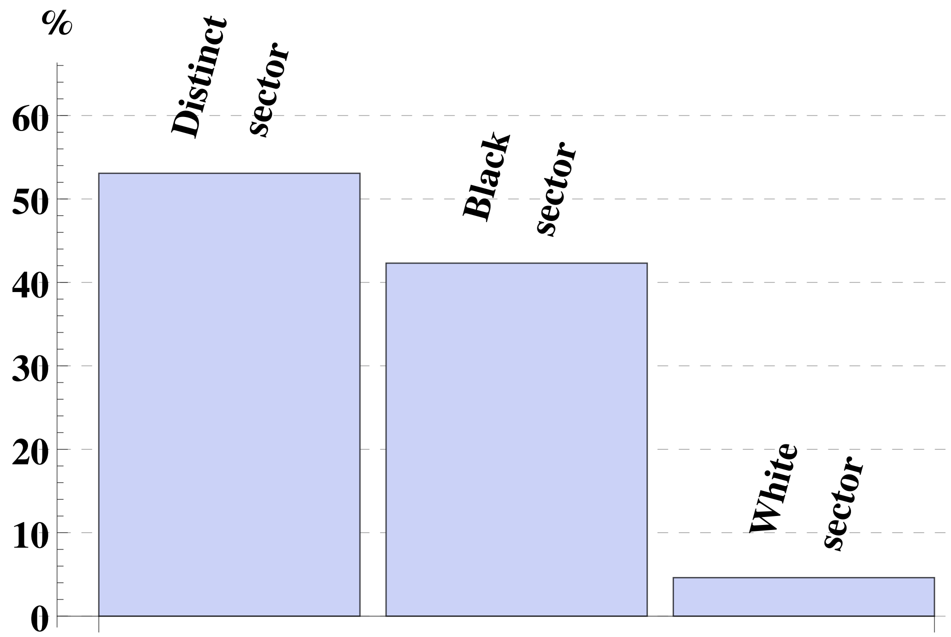

Figure 6: Results of the Coordination Treatment

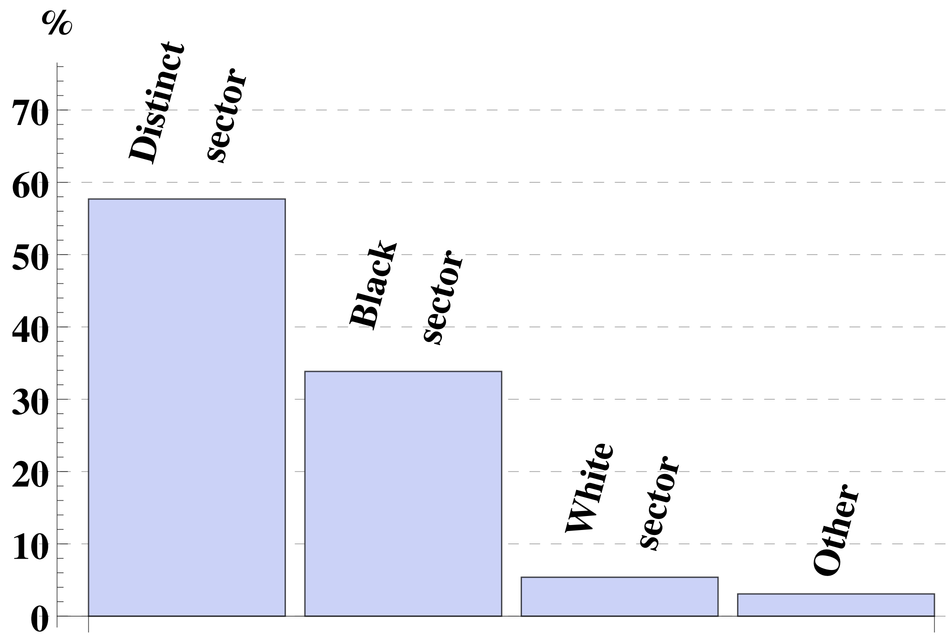

Figure 7: Results of the Self Treatment

These results are in line with Blume and Gneezy's (2010) results where around 52% (58% in our experiment) have been able to identify the distinct sector and around 23% (34%) have chosen the black sector. We contribute the significantly lower level of noise (8% vs 25%) to the extensive instructions and the quiz we conducted before the experiment.[14]

Due to the lower level of noise we are, unlike Blume and Gneezy (2010), able to use a within-subject design, in which each player has access to 625 possible strategies.[15] Of these strategies we consider 96.32% as "noise".[16] As the number of strategies which support our hypothesis are very low (1, 4 and 2 out of 625), the probability that someone chooses them by mistake is very low. For a detailed overview of all possible strategies and how we categorize them see Table 1.

[14]For the instructions and an overview of the quiz see the Online Appendix.

[15]We are here ignoring the order in which treatments are played.

[16]This noise includes not only players not understanding the experiment or behaving randomly but also "Eureka"-learning (which was a big problem in Blume and Gneezy (2010), see Appendix C), making a mistake (e.g., picking a not distinct white sector instead of the distinct sector, a mistake, which both of the authors made multiple times while testing the experiment) and beliefs of low-cognition players.

Description	Hypothesis	# of strategies	Proportion
DD D D	1: Coordination is possible	1	0.16%
DD B B	2: First-order beliefs matter	4	0.64%
DD D B	3: Higher-order beliefs matter	2	0.32%
BB B B	(Low-cognition players)	16	2.56%
"Noise"	-	602	96.32%
WW-W-W	(part of "Noise")	80	12.80%

Table 1: Overview of the strategies

Given the preliminaries, we can test hypotheses 1 through 3.

Hypothesis 1 (Coordination is possible)**.** *High-cognition players choose in the coordination treatment D more often than any other choice.*

The choice data from our experiment confirms this hypothesis. In Figure 8 we can see that 80% have chosen the strategy "DD D D". As this strategy represents only 0.16% of all available strategies (or 4% when excluding the Self Treatment), we can reject the null hypothesis of this high level of coordination being a result of random play ($p < 0.00001$).

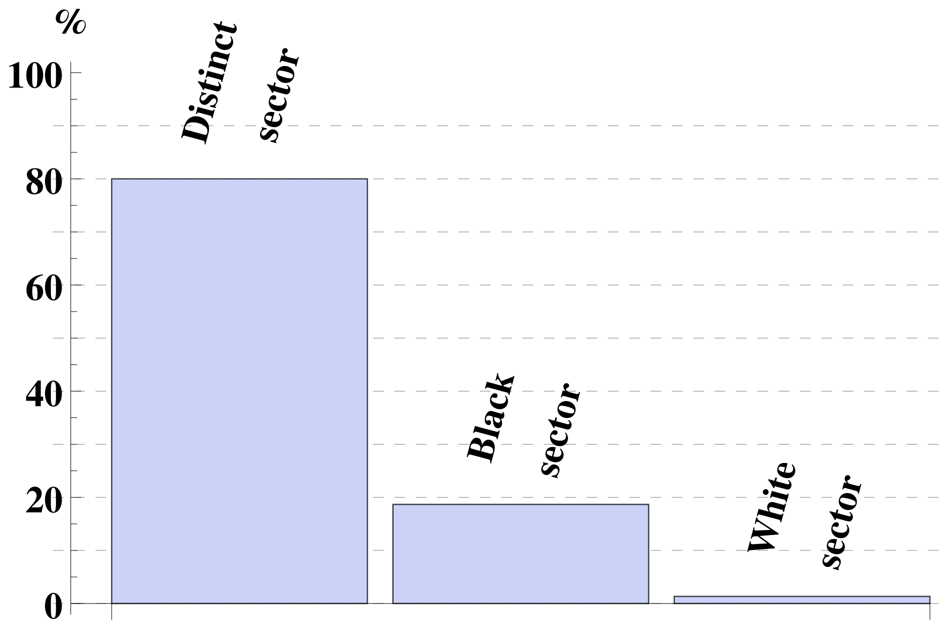

Figure 8: Results of the Coordination Treatment (high-cognition players)

Blume and Gneezy (2010) claim that "beliefs matter" and we test in Hypothesis 2 if there are subjects whose pessimistic beliefs about the other players' skills lead to coordination failure.

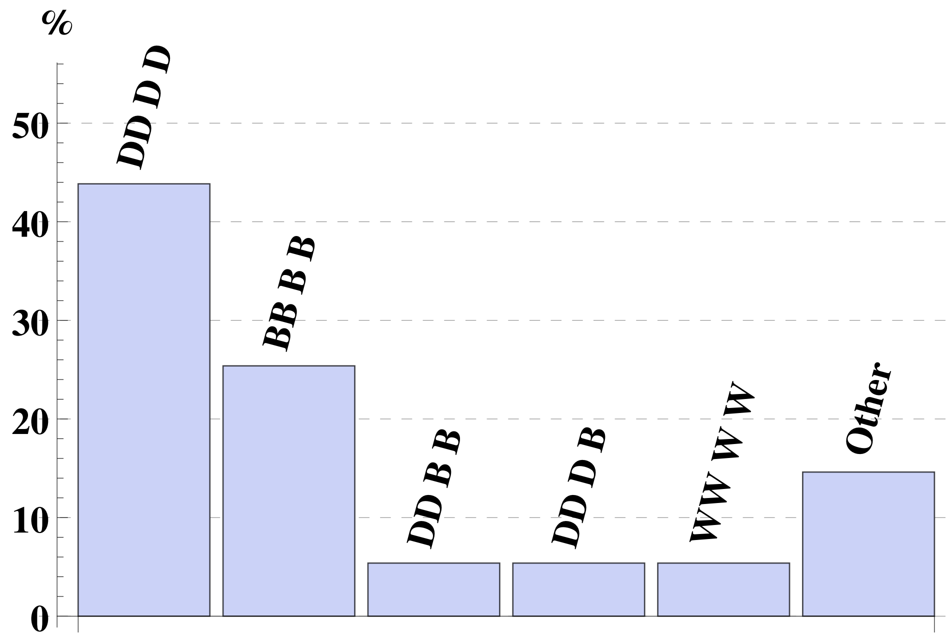

Figure 9: Used strategies

Hypothesis 2 (First-order beliefs matter)**.** *There are high-cognition subjects who choose a black sector in the Prediction Treatment and Cooperation Treatment, i.e., play "DD B B".*

Our data confirms this hypothesis. Figure 9 shows us the results of all players, Figure 10 of the high-cognition players. In these figures we can see that about 9% of the high-cognition players (or 5% of all players) have a first-order belief problem, leading to coordination failure. As the fraction of strategies leading to this conclusion is very small (0.64%) we can reject the null hypothesis that this result is due to chance ($p < 0.00001$).

But do players really use higher-order beliefs in this type of games? Hypothesis 3 tests for this question.

Hypothesis 3 (Higher-order beliefs matter)**.** *There are high-cognition subjects who play the distinct sector in the Prediction Treatment and a black sector in the Cooperation Treatment, i.e., play "DD D B".*

From Figure 9 and Figure 10 we can see that there are high-cognition players who think that their partner is with a high probability of the high type, they, however, still think there are coordination problems. Again, we can reject the null hypothesis at the 1% level ($p < 0.00001$).

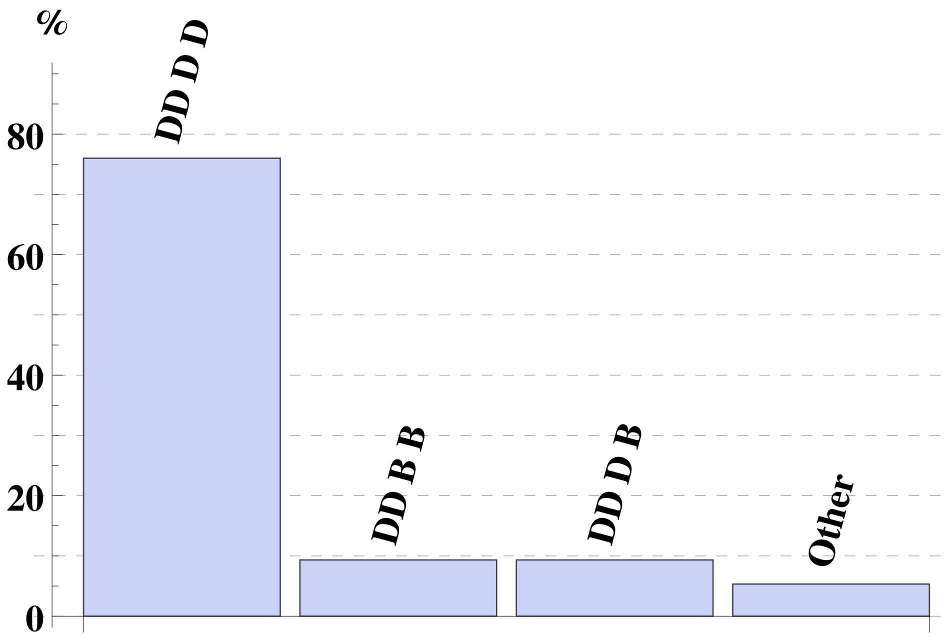

Figure 10: Used strategies (high-cognition players)

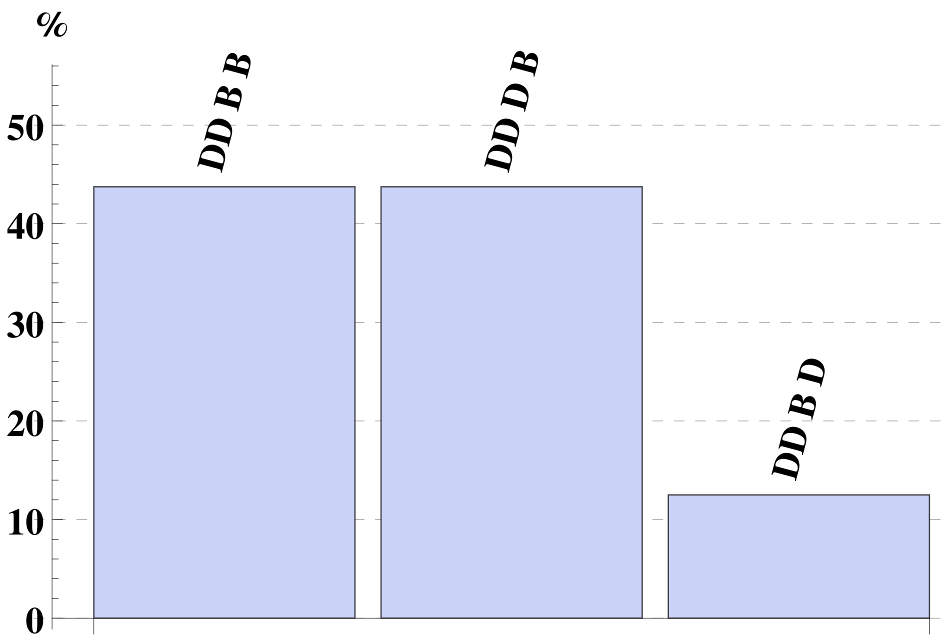

Figure 11: Robustness check

Hypothesis (Robustness check)**.** *"DD B D" is played less often than "DD B B" and "DD D B".*

All these results are statistically significant at the 1% level, however, our design allows for another robustness check: There is a strategy which should not be played by rational players: "DD B D", which is about as likely to be picked at random as ″DD B B“ and ″DD D B“ but can not be explained by our model. Figure 11, shows us that only 2 subjects have chosen this strategy.

We expected to have significant order effects, as in Blume and Gneezy (2010). However, it turns out, that the only robust order effect is a weak effect in the Self Treatment (i.e., more subjects have been able to choose the distinct sector twice later in the experiment).[17] We attribute this to a small change in design. We have explained every treatment before the experiment started and we have conducted a quiz (Section E.2), testing if the instructions have been understood. This probably lead to ″Eureka learning“ before instead of during the experiment.

6. The role of beliefs in the fight against female genital mutilation

More important applications than the search for ones husband or wife in a department store are suggested by recent studies in sociology and development studies, for example by Bicchieri (2005).[18] She claims that common knowledge plays a significant role in the fight against female genital mutilation.[19] Female genital mutilation is practiced in, predominately African, communities and is required in many of these communities to find a husband and to prevent social exclusion. Despite being very dangerous and unnecessary, it has a long standing tradition and is, in areas where it is still practiced, very common. It is estimated to effect up to 200 million women in 2016 (UNICEF (2016)). In game theoretic terms the problem is one of equilibrium selection: There is one equilibrium in which everyone accepts and uses female genital mutilation and one in which no one does. The latter equilibrium is, given enough knowledge about the subject, clearly better for everyone, but we still observe the former equilibrium in many communities.

An important tool in the fight against female genital mutilation is to inform people about the dangers and (lack of) benefits of it. However, studies like Bicchieri (2005) suggest that just educating might not be enough. She claims that common knowledge of this education plays an important role because negative beliefs about the opinion of the other members of a community might prevent a coordination on the better equilibrium (i.e., the one without female genital mutilation): Even if I am convinced that this practice should be abolished, I might still partake in it, to prevent my daughters from being excluded from the community,

[17] For the full analysis of order effects see Appendix C.

[18] More examples in which common knowledge plays an important role can be found in Chwe (2013).

[19] Most studies, however, don't use the terms "beliefs" or "common knowledge" but describe this concepts in their own words, frequently restricting their attention to first-order and therefore ignoring higher-order beliefs.

as the others might not be convinced (i.e., my first-order belief is that others have not been educated). I also might think that others will continue this practice because they think I wasn't educated (i.e., because of my second-order belief) and so on.

That means, that just educating a family (or, in game theoretic terms: changing their type) does not necessarily lead them to change their stance on female genital mutilation. But is there any evidence that families use beliefs? Mackie (1996) and Mackie and LeJeune (2009) have compared the old Chinese tradition of foot binding[20] and female genital mutilation and pointed out that both are similar: Both are required to find a husband, while being very painful and dangerous without having any known benefits. Furthermore, they have a long-standing tradition (both can be traced back more than 1000 years) and were widely spread in their respective cultures. However, around 1910, foot binding has dropped in certain parts of China from 99% to under 1% prevalence over the course of just 20 to 30 years, without any change in policy (Gamble (1943), Keck and Sikkink (1998)), whereas even a combined effort of the UN, several NGOs and governments over the last 40 years resulted only in a moderate decline from about 51% to 37% of women effected by female genital mutilation in certain countries (UNICEF (2016)). Mackie (1996) claims that the main difference is the method of information transmission: In China, societies have been founded in which members publicly pledged to not bind their daughters' feet and to prevent their sons from marrying women with bound feet, whereas the effort to prevent female genital mutilation was mainly focused on changing the laws and educating the people about the dangers and problems. The societies fighting foot binding made the education and position of the families common knowledge whereas most organizations fighting female genital mutilation focused on changing the opinion of the families without changing the higher-order beliefs much.

But also between projects fighting female genital mutilation there have been differences. Tostan, a Senegal-based NGO, has, according to World Bank Group (2012) successfully reduced the number of female genital mutilation in some parts of Senegal significantly. So, why did Tostan succeed where others have failed? They claim that not only education but " [...] public declarations are critical in the process for total abandonment [of female genital cutting.] " (Tostan (2016)) and are supported by World Bank Group (2012) who emphasizes that education together with public discussion and public declaration was an important factor in Tostan's success.

These examples suggest that beliefs might play an important role, as the more

[20] Foot binding was a Chinese practice of bending and binding the four lower toes of young girls tightly under the foot.

successful campaigns against foot binding and female genital mutilation also addressed higher-order beliefs by introducing common knowledge whereas others who focused on pure education have been less successful. However, it is not clear that common knowledge is required to achieve coordination. It might be sufficient to explain that others have also been educated (i.e., to take care of the first-order beliefs), which would be much cheaper than providing common knowledge.

However, from our results we know that ignoring the higher-order beliefs can have severe negative consequences. Our results can explain why education without considering problems due to higher-order beliefs can have some effect but they can also explain why NGOs like Tostan have significantly more success. Furthermore, these results give reason to belief that only explaining if others have been educated and are against female genital mutilation (i.e., changing the first-order beliefs) might not be sufficient and making this education common knowledge might be necessary to achieve all possible benefits from it.

However, the results from this experiment conducted with students at a European university should of course not be generalized to explain behavior in small rural communities without further research but gives us reason to belief that higher-order beliefs do matter.

7. Conclusion

We have seen that, in this game, absence of common knowledge was not enough to prevent to choose the Pareto-dominant equilibrium strategy, as 76% of the high-cognition players have chosen the Pareto-dominant equilibrium strategy. However, we still have a fraction of players who have beliefs that lead to coordination failure (around 18%) and of these only half could be attributed to first-order beliefs.

Of the models of higher-order beliefs discussed in Section 4.2 and Appendix B, only "assuming common knowledge" or a common p-belief were able to explain coordination on the payoff-dominant equilibrium. However, these assumptions can not explain any coordination failure due to beliefs, as the beliefs are fixed by the model, whereas the models which can explain this type of coordination failure predict playing the payoff-dominated strategy.

Therefore, as we have observed a coordination rate of about 76%, assuming common knowledge (or a common p-belief) might be the best tractable approximation available in coordination games without common knowledge, depending on the focus of the research.

Our work opens up some questions for future research: Can these results be generalized to other populations and environments? Are there certain parts of the populations who are more likely to exhibit first- or higher-order beliefs which lead to coordination failure? Are there other, maybe easier methods to make something common knowledge? Furthermore, it might be worthwhile to check more general structures of higher-order beliefs or if non-equilibrium models like Strzalecki (2014) or Kneeland (2016) can explain this phenomenon better.

Appendix A Belief hierarchies

Let $B_i^0 := T_j$ and $B_i^k = T_j \times \Delta(B_i^{k-1})$ with $\Delta(B)$ being the space of probability measures on B and $\Delta(X)$ being the space of probability measures on the Borel field of X, endowed with the weak topology. Using this notation, we can define a belief hierarchy as follows.

Definition 3 (Belief hierarchy)**.** A *k-th order belief* is defined as

$$b_i^k \in \Delta(B_i^k)$$

with $B_i^0 = T_j$ and $B_j^k = T_j \times \Delta(B_j^{k-1})$
Furthermore, let us set $b_i^0 := t_i$.
A belief hierarchy of a player i is then $b = \{b_i^0, b_i^1, \ldots.\}$

We therefore have a first order belief $b_i^1 \in \Delta(\{low, high\}) = [0,1]$ and higher-order beliefs $b_i^k \in [0,1]^k$.

Furthermore, we assume these beliefs to be coherent, i.e. that beliefs of different orders do not contradict one another,[21] and that a low-cognition type does not know about higher cognitive types, i.e., $b_i^k = 0 \Rightarrow b_i^{k+1} = 0 \quad \forall k \geq 0$.

This excludes, on the one hand, that a low-cognition player thinks that the other player is a high-cognition player and, on the other hand, that a player has a first-order belief that the other player is of a the high type and a higher-order belief that the player is of the low type.

Appendix B Equilibrium selection and models of higher-order beliefs

In this section we are going to discuss how different models of beliefs and frequently used assumptions on the structure of higher-order beliefs influence the specific game we analyze.

Using the results from the literature on focal points in coordination games (as discussed in Section 1.1), we know that we can restrict our attention on the two actions with the highest payoffs a_{m-1} and a_m. This simplifies the game to a Bayesian game with two types, a low type whose only attainable action is a_{m-1} and a high type, who has access to a_{m-1} and a_m, without common knowledge about the type distribution. Then, we can denote, with a small abuse of notation, the strategy of a player as the action she chooses if she is of the high-type, i.e., a_m or a_{m-1}, knowing that she will play a_{m-1} if she is of the low type.

[21] I.e., higher-order beliefs of a player mapped onto the space of beliefs of a lower order are the same.

Let us first start with the most common assumption, that the *distribution of types is common knowledge*. Then the expected utility of a (risk neutral) high-cognition player is as depicted in Table 2, given her and her partners strategies.[22] p denotes here the probability of a player being of the high type. We can see that the prediction of the model then depends on p. If the probability of a player being of the high type p is too low ($p < \frac{x_{m-1}}{x_{m-1}+x_m}$), only (a_{m-1}, a_{m-1}) will be an equilibrium. In this paper we are going to assume that $p \geq \frac{x_{m-1}}{x_{m-1}+x_m}$ which makes sure that the "better" equilibrium always exists.[23] For risk-averse players, it is required that $p \geq \frac{u(x_{m-1})}{u(x_{m-1})+u(x_m)}$, so we know that as long as $p \geq \frac{1}{2}$ the high-type equilibrium always exists, independently of the degree of risk aversion. Furthermore, if the equilibrium exists, it is payoff dominant.

	a_{m-1}	a_m
a_{m-1}	x_{m-1}, x_{m-1}	$(1-p)x_{m-1}, 0$
a_m	$0, (1-p)x_{m-1}$	px_m, px_m

Table 2: Expected utilities of two high-cognition players

Therefore, the prediction of assuming that the *distribution of types is common knowledge* is that, for a high-enough p, we should expect full cooperation.

Monderer and Samet's (1989) *common p-belief* is a generalization of the concept of common knowledge and generates, in this model, the same predictions as assuming that the distribution of types is common knowledge, given a high-enough p.

The game we are analyzing is very close to the original description of a global game as introduced by Carlsson and Van Damme (1993). Written down as in Table 2 it is a very similar game as the main example used in Carlsson and Van Damme (1993). Therefore, we know that, given $\frac{x_{m-1}}{x_m} \leq p \leq \frac{2x_{m-1}}{x_m+x_{m-1}}$ (i.e., (a_m, a_m) is still a Nash equilibrium but (a_{m-1}, a_{m-1}) is risk dominant), (a_{m-1}, a_{m-1}) will be the only rationalizable solution to the global game. Furthermore, Hellwig (2002) shows that higher-order uncertainty about preferences leads to results similar to Carlsson and Van Damme's (1993) higher-order uncertainty about payoffs, i.e., coordination on the "less risky" equilibrium.

Rubinstein (1989) shows that truncating common knowledge at any finite level is equivalent to the situation without any common knowledge at all and therefore suggests that players choose the save strategy a_{m-1}.

[22]In the analysis we restrict our attention to risk-neutral players. However, the analysis for the case of risk-averse players is analogous and the experimental results are valid for every possible degree of risk aversion.

[23]In the experiment this assumption requires $p > \frac{1}{3}$. As the fraction of high-cognition players is 58%, this assumption is not problematic.

Model	Coordination	First-order belief coordination problems	Higher-order belief coordination problems
Common knowledge	Full coordination	No	No
Common p-belief	Full coordination	No	No
Global games	No coordination	Yes	Yes
Almost common knowledge	No coordination	No	Yes.

Table 3: Models of higher-order beliefs

Weinstein and Yildiz (2007a) establish a condition, called "global stability under uncertainty" which implies that the change in equilibrium actions is small in the change of kth-order beliefs and higher. Therefore, under this condition, equilibria can be approximated by the equilibrium with lower-order beliefs. Unfortunately, pure coordination games do, in general, not fulfill the conditions for "global stability under uncertainty" as the best responses are very sensitive to every order of beliefs and even a small change in some higher-order belief might make a player change from a_m to a_{m-1}.

Appendix C Order effects

Earlier, we have briefly discussed an uncertainty principle, in which higher-order beliefs can not be measured without inducing them. This theory is a related to the "good subjects hypothesis" (Orne (1962)) according to which some subjects try to figure out the research question and then change their behavior to confirm said hypothesis. However, in this case the difference is more subtle: As soon as they realize that there is a higher-order belief problem, they might overestimate it.

Blume and Gneezy (2010) have encountered a different case of this uncertainty hypothesis. "Having a player play against himself may trigger an insight that switches a player from low to high cognition ("Eureka!" learning). There may be an uncertainly principle at work here in that we cannot measure a player's cognition without altering it." (Blume and Gneezy (2010)) This suggests, that the order of treatments might be important. Therefore, we implemented a random order. However, it turns out that we have (almost) no order effect, as can be seen in Table 4. The only statistically significant effect is that, if the self treatment was the first treatment, there was a significantly higher number of "Other" results than when it was the second ($p = 0.0062$) or third treatment ($p = 0.0139$). Furthermore,

Treatment	Self			Prediction			Coordination		
Order	**DD**	**BB**	**Other**	**D**	**B**	**W**	**D**	**B**	**W**
1st	18	10	8	23	15	3	22	22	3
2nd	32	24	2	20	16	2	24	10	0
3rd	25	10	1	32	15	4	23	15	5

Table 4: Order effects of the different treatments

the distinct sector was played more often in the coordination treatment if it was the second than the first treatment ($p = 0.0277$), however, there were no significant effects when comparing the first and third and the second and third.[24] The former has a intuitive explanation (i.e., practicing the task makes it less likely to make a mistake) whereas the later is considered to be a type II error by the authors.

The question now is, why did Blume and Gneezy (2010) encounter strong "Eureka!"-learning effects whereas we had (almost) no significant effect. The authors attribute this to the fact that we used more extensive instructions and a quiz to make sure the instructions where understood. More importantly, the participants were instructed in all three treatments before they played the first game which most likely triggered the learning before the first decision, whereas in Blume and Gneezy (2010) the instructions for the second treatment were distributed after completion of the first treatment.

[24]Using the one-tailed Fisher's exact test.

Appendix D Data

For the complete data set please refer to the Online Appendix.

Self		Guessing	Coordination
D	D	D	D
D	D	D	D
D	D	D	D
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D	D	D	D
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W	W	W	W

Table 5: Strategic choice data

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Appendix E Online Appendix

E.1 Instructions

Welcome to this experiment in economic decision making. It will take approximately 60 minutes. First of all, please check that the number on the card handed to you matches the number on the cubicle that you are seated in and that your mobile phones are turned off.

Before we start, we will explain the rules of this experiment. You will also find these rules on the paper provided, so you can read along and check again during the experiment. If you have any questions, please do not speak up but raise your hand and we will come to you and answer your question privately.

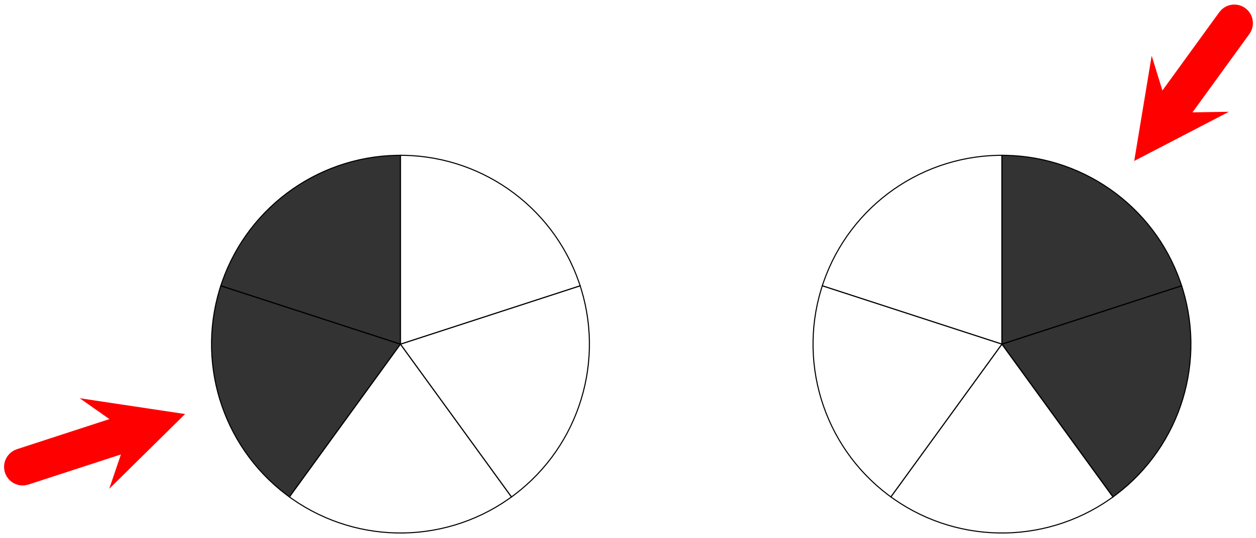
From now on, please do not talk, and listen carefully. In this experiment you will earn a minimum of £3, and potentially up to £18. How much money you earn will depend on your decisions and those of the other participants. Your reward will be paid out at the end of the experiment. None of the other participants will know how much money you made.

In this experiment you will be asked to make decisions related to a disc that has 5 sectors, similar to the disc provided to you. The disc has two identical sides. Your goal will be to pick the same sector twice (more on that later). During this experiment the disc will be flipped and/or rotated randomly.

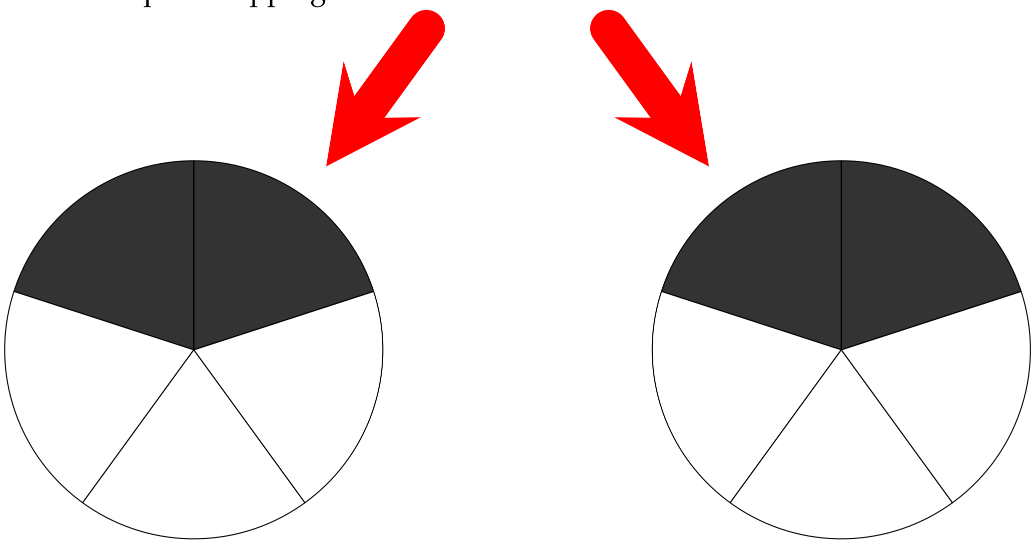
Pictures on page 2 illustrate rotation and flipping. Since you will not be told if the disc was flipped and/or rotated, it might even be the case that disc looks exactly the same though sectors have changed their positions.

The arrow tracks one specific sector that changes its position as the disc is rotated and/or flipped.

This is an example of rotating the disc by two sectors:



This is an example of flipping the disc:

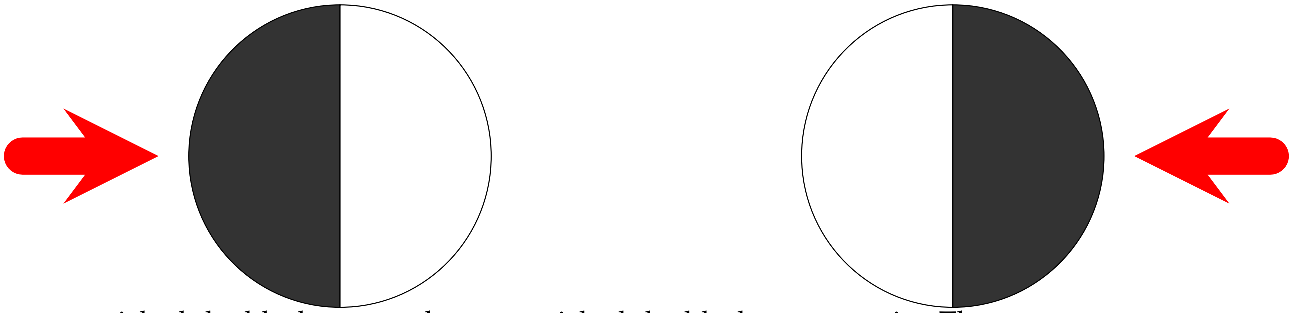


In the experiment the disc will be surrounded by the letters A, B, C, D, and E. **These labels are not part of the disc!** They are only included to allow you to choose a sector.

In the experiment you will make decisions in the following environments (the order will be chosen randomly):

(**Self Game**) You will be asked to pick a sector twice; first you choose a sector; then the disc might be flipped and/or rotated. After this you are shown the same disc and have to choose a sector again. You will not observe the flipping/rotation of the disc. If you manage to guess the same sector twice, your payoff will be £5. Otherwise, you will receive 0. Therefore, to earn more money you want to maximise your chances to pick the same sector twice.

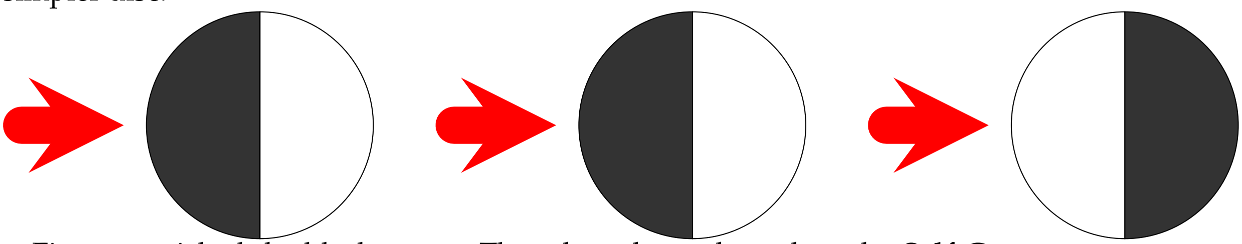
Here is an example of the choices made in a **Self Game**, using a simpler disc with only 2 instead of 5 sectors:



First you picked the black sector; then you picked the black sector again. Therefore, you pick the same sector twice and earn £5.

(**Prediction Game**) You are matched randomly with another person and you have to guess the choice of this person, while she plays the **Self Game**. First, you choose a sector on the disc; each time the other person picks the sector you chose, you will receive £2.5. As the other player picks twice in the **Self Game**, you can earn £0, £2.5 or £5 in this situation, depending on your and the other person's choice. Therefore, to earn more money you want to guess what the other player is playing in the **Self Game** described above.

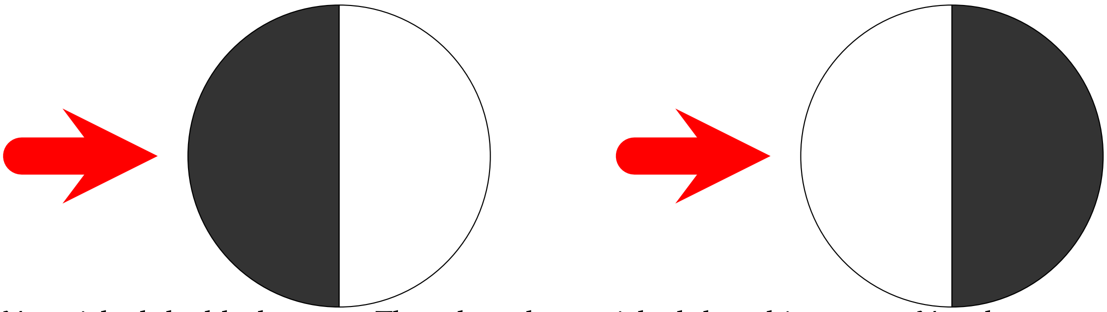
Here is an example of the choices made in a **Prediction Game**, again with the simpler disc:



First you picked the black sector. The other player then plays the **Self Game**. He first picks the black sector and therefore you earn £2.5. Then he picks the white sector and therefore you earn £0. Thus you earn £2.5 in total.

(**Coordination Game**) You are matched randomly with another person and both of you are asked to pick a sector on the disc simultaneously. Both of you know that you play the **Coordination Game**. You both see the same disc but possibly differently flipped and rotated. If both of you pick the same sector, then your payoff will be £5. Otherwise, you will receive £0. Therefore, to earn more money you want to guess the sector your partner is picking here, while he is trying to do the same.

Here is an example of the choices made in a **Coordination Game**, again with the simpler disc.



You picked the black sector. The other player picked the white sector. You therefore failed to coordinate and both of you earn £5 each.

The experiment consists of two periods. Each period consists of the three games as described above, using a 5-sector disc; the order of the games is random. At the end of the experiment one of the two periods will be randomly chosen. The earnings made in this period will be paid out in cash.

Again, please do not talk during this experiment! If you have questions just raise your hand.

Before the experiment there will be a quiz to check your understanding. Read hints carefully if you get stuck during the quiz.

E.2 Quiz

In this appendix you can find screenshots of the quiz which was conducted before the experiment. Participants who made a mistake in some part of the quiz were given a small hint and then were asked to repeat this part of the quiz.

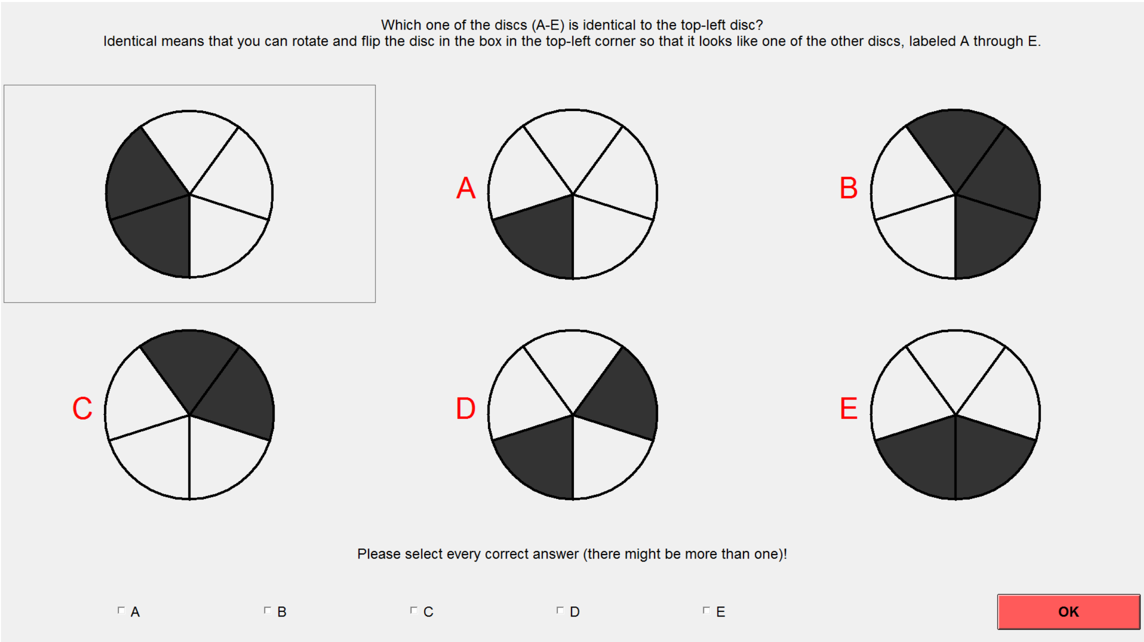


Figure 12: Quiz part 1

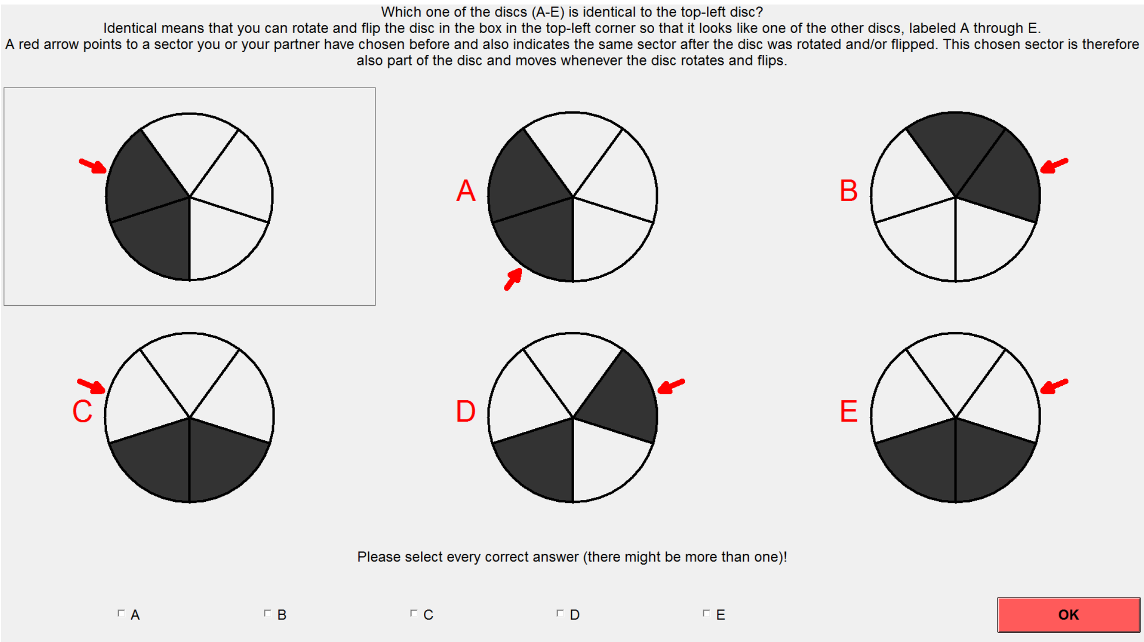


Figure 13: Quiz part 2

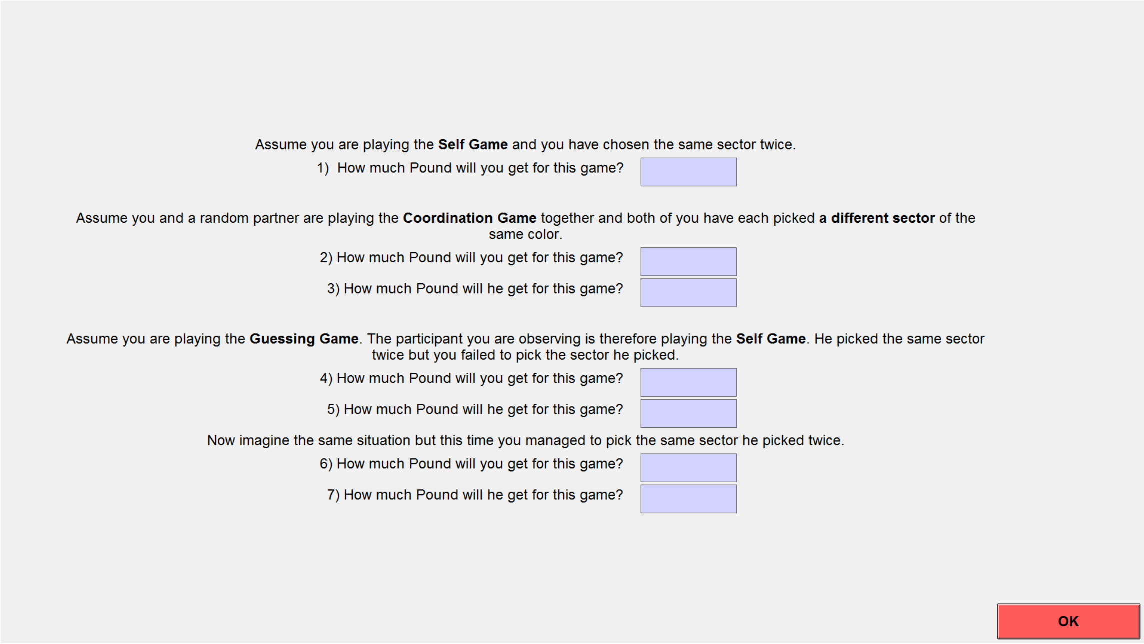


Figure 14: Quiz part 3

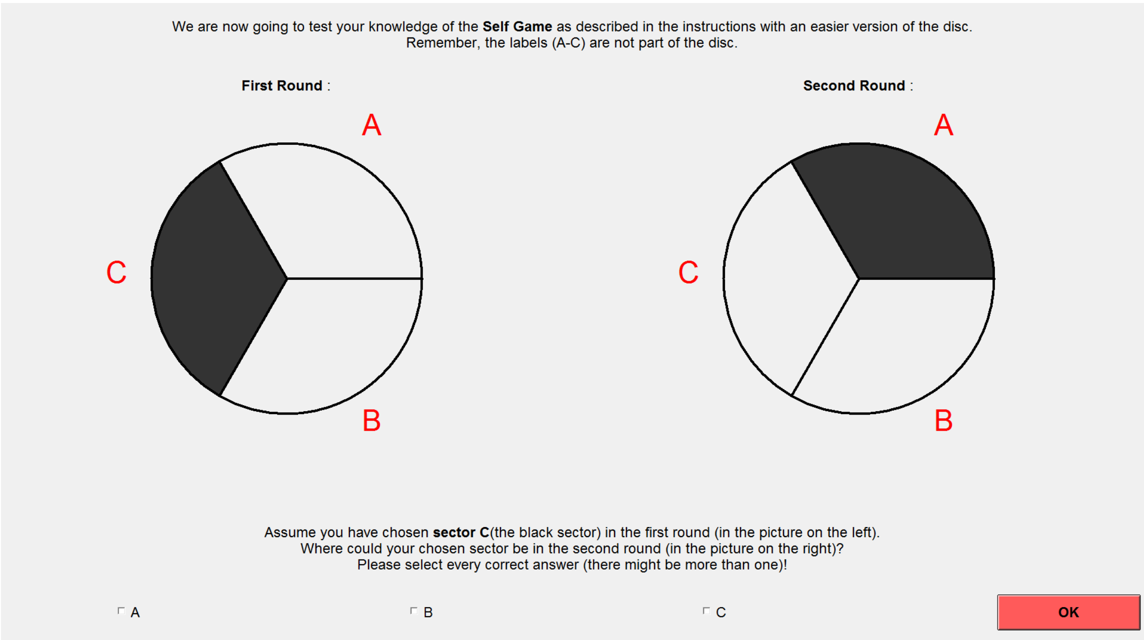


Figure 15: Quiz part 4

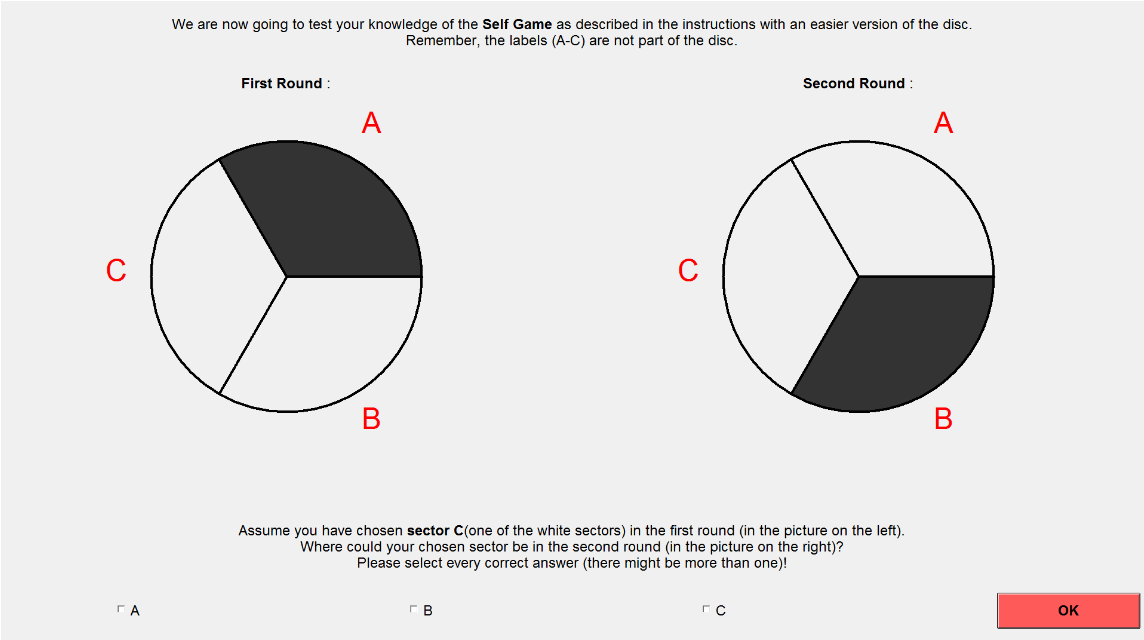


Figure 16: Quiz part 5

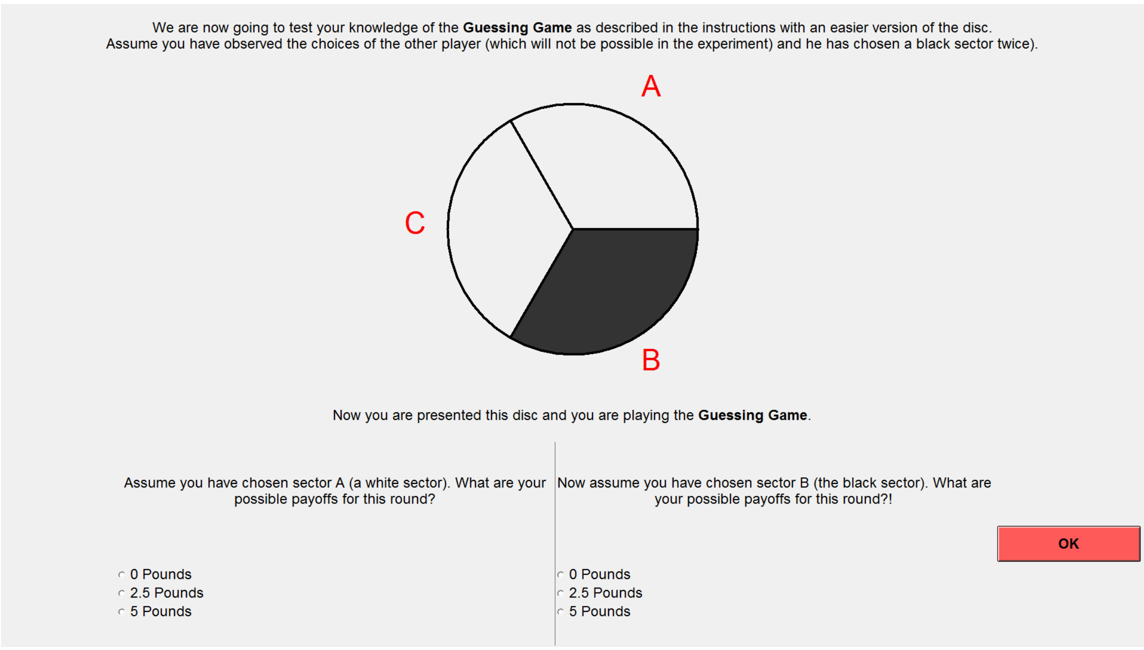


Figure 17: Quiz part 6

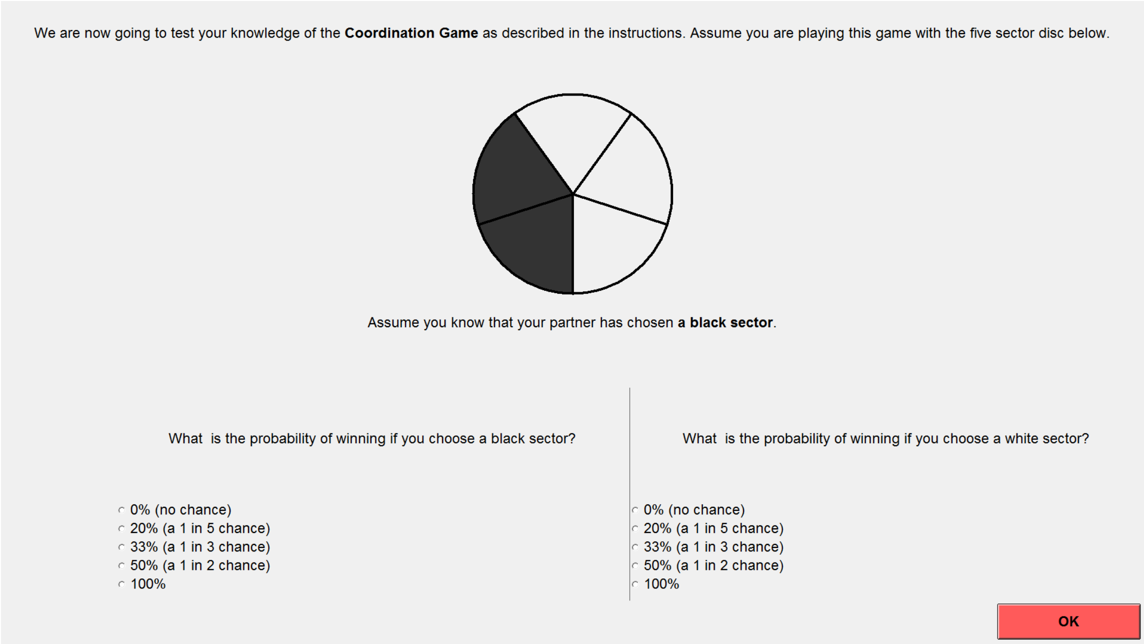


Figure 18: Quiz part 7

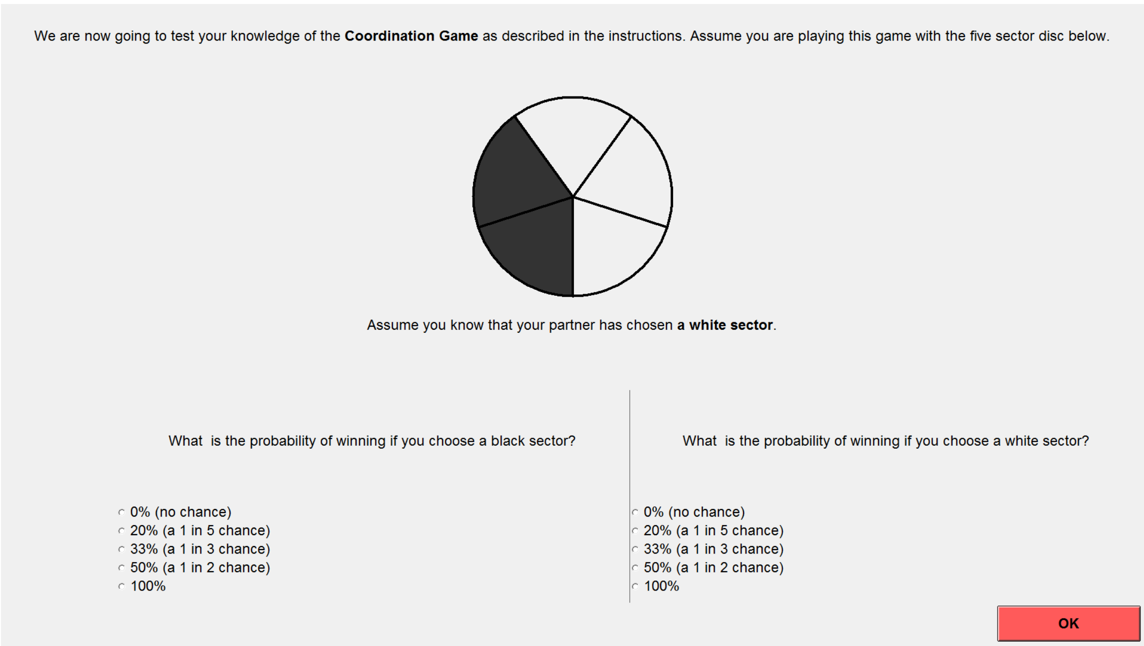


Figure 19: Quiz part 8