An Experimental Study Of Uncertainty In Coordination Games

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Abstract

Global games and Poisson games have been proposed to address equilibrium indeterminacy in Common Knowledge Coordination games, where fundamentals are commonly known by all players. Global games assume that agents face idiosyncratic uncertainty about economic fundamentals, whereas Poisson games model the number of actual players as a Poisson random variable to capture population uncertainty in large games. The present study investigates in a controlled setup, using as controls Common Knowledge Coordination games, whether idiosyncratic uncertainty about economic fundamentals or uncertainty about the number of actual players may influence subjects' behavior. Our findings suggest that uncertainty about the number of actual players has a more significant impact on subjects' behavior than idiosyncratic uncertainty about economic fundamentals. Furthermore, subjects' behavior under Poisson population-size uncertainty is closer to the respective theoretical prediction than subjects' behavior under idiosyncratic uncertainty about economic fundamentals.

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1 Introduction

Coordination games with strategic complementarities have been widely used to capture setups, such as speculative attacks, start-up investments and new technology adoption under network externalities (see e.g. Milgrom and Roberts (1990), Obstfeld (1996)). If the state of the economy (i.e. profitability of the risky action) and the number of stakeholders/players is common knowledge, then, equilibrium cannot always be pinned down uniquely because beliefs can be indeterminate. To escape a prediction of indeterminancy of equilibria, the received theoretical literature has focused on uncertainty about fundamentals (see e.g. Morris and Shin (1998), Herrendorf, Valentinyi, and Waldman (2000), Frankel and Pauzner (2000), Burdzy, Frankel, and Pauzner (2001) and Makris (2008)).

Global Coordination games (see Morris and Shin (1998)) constitute the most popular approach to escape the prediction of equilibrium indeterminacy by means of deploying uncertainty about economic fundamentals (e.g. the profitability of a successful speculative attack). A more recent approach, Poisson Coordination games, is motivated instead by the fact that, in the above strategic environments, the number of economic agents is often *very large*. As Myerson (2000) points out, in games with a very large number of players, "it is unrealistic to assume that every player knows all the other players in the game; instead, a more realistic model should admit some uncertainty about the number of players in the game" (p. 7). Following the suggestion of Myerson (2000), this approach models the number of actual players as a Poisson random variable (see Makris (2008)).[1]

Importantly, Global and Poisson Coordination games lead to different predictions. The Global Coordination game prediction about, say, the onset of speculative attacks manifests a threshold level of economic fundamentals that defines two areas in the region where Common Knowledge Coordination games predict multiplicity of equi-

[1]This modelling choice is driven, in part, by certain convenient properties of the Poisson distribution (see Myerson (1998)). As a complementary justification for this modelling choice, suppose that the identity of every stakeholder is common knowledge and that binding individual orders for, say, short sales of a currency must arrive with the central bank by a given time. Standard theory suggests that each agent will decide on her action by taking the number of orders at the collector's disposal as given. However, the probability that a phone call to a busy switchboard will go through or the webpage of an online site will be uploaded successfully at times of high traffic decreases with the number of stakeholders. As a result, and under the assumption that the average number of successful phone calls or online visits is known, in a large environment, stakeholders should actually view the number of actual players in the Coordination game as a Poisson random variable.

libria: one in which a successful attack takes place, and another, where a successful attack does not materialize. However, the Poisson Coordination game prediction is that no speculative attack will take place as long as the ratio of the short-selling cost per reward is greater than the probability of having sufficiently many players in the game; otherwise, multiplicity of equilibrium outcomes still arises (see Section 3 for more details).

Motivated by the aforementioned theoretical papers, the present study investigates in a controlled setup, using as controls Common Knowledge Coordination games, whether idiosyncratic uncertainty about economic fundamentals or uncertainty about the number of actual players may influence subjects' behavior. Specifically, we design a novel experiment to compare the behavior of subjects in Poisson, Common Knowledge and Global Coordination games (henceforth, for brevity, referred to as *Poisson*, *Common Knowledge* and *Global games*, respectively, unless there is a risk of confusion). The experimental design is formulated around asking subjects to state their intent to buy a cash amount.[2] Registering to buy the cash amount entails paying a non-refundable fee, which is less than the cash amount. Additionally, in order to get the cash amount, a threshold number of registrations has to be met. If fewer subjects than the number dictated by the threshold register, then, the cash amount is not awarded.

We make three key contributions in this paper. First, to the best of our knowledge, we are the first to provide an experimental investigation of Poisson Coordination games. Games assuming Poisson population-size uncertainty have been studied theoretically in mostly Voting games (see e.g. Krishna and Morgan (2011), Bouton and Castanheira (2012), Medina (2013), Bouton and Gratton (2015)) and Discrete Public Goods games (Makris (2009)). The only other experimental studies of Poisson games we know of are those of Ostling, Wang, Chou, and Camerer (2011) and Herrera, Morelli, and Palfrey (2014). Ostling, Wang, Chou, and Camerer (2011) study the Swedish Lowest Unique Positive Integer (LUPI) game, and find that the behavioral patterns of the field and laboratory data are closely related with the theoretical predictions. Herrera, Morelli, and Palfrey (2014) investigate a voter turnout model, where they compare the turnout in two electoral systems: a winner-takes-all system,

[2]In the lingo of the speculative attack model of Morris and Shin (1998), registering to buy the cash amount is analogous to short selling the currency. Alternatively, in the context of investors and technology adopters under network externalities, registering to buy the cash amount is analogous to undertaking the investment opportunity and adopting the new technology, respectively.

and a proportional power sharing system. Their results from a laboratory experiment are broadly supportive of the theoretical predictions.

The second key contribution of our study is methodological. Specifically, our experiments are conducted over the Internet. Internet is ideal for Poisson games as subjects cannot infer the number of participants, which is typically the case in a laboratory experiment. Crucially, in order to circumvent the difficulties that would arise given the (assumed) unfamiliarity of many subjects with Poisson probabilities, we applied the specific probabilities onto a roulette wheel and noted that the latter is not a standard wheel. In order to maintain consistency with the Poisson experiments, the Global and the baseline (i.e. Common Knowledge) sessions were also conducted over the Internet while accommodating the underlying assumptions of the theories. A value-added of this approach is that it resembles how managers and investors commit to their decisions nowadays: after contemplating the pros and cons of various alternatives, managers and investors will often place their (short-selling, purchase or investment) orders online.

Our third and most important contribution is substantive. We find that uncertainty about the number of actual players has a more significant impact on subjects' behavior than idiosyncratic uncertainty about economic fundamentals when we focus on parameters for which both Poisson and Global games predict a unique equilibrium. Specifically, we find that, in their vast majority, subjects in the Poisson games forego to register to buy the cash amount (i.e. choose the 'safe' action), whereas in both Global and Common Knowledge games, subjects split almost evenly between foregoing registering to buy the cash amount and registering to buy the cash amount. Therefore, the introduction of uncertainty regarding the number of actual players may influence empirical behavior in large environments with strategic complementarities, whereas the introduction of idiosyncratic uncertainty about economic fundamentals may not. Finally, subjects' behavior under Poisson population-size uncertainty is closer to the respective theoretical prediction than subjects' behavior under idiosyncratic uncertainty about economic fundamentals.

The paper adheres to the following plan. We present next other related experimental literature. In Section 3, we review the theoretical predictions of Common Knowledge, Global and Poisson games. In Section 4, the experimental design is presented. In Section 5, we report the results of our experiments. In Section 6, we conduct a robustness analysis and in Section 7, we discuss comparative statics and a possible explanation for the main results based on limited depth of reasoning. Finally, in Section 8, we conclude and offer suggestions for future research.

2 Other Related Experimental Literature

Common Knowledge Coordination games have been studied extensively experimentally (see e.g. Van Huyck, Battalio, and Beil (1990), Van Huyck, Battalio, and Beil (1991), Van Huyck, Battalio, and Beil (1993), Brandts and Cooper (2006), Cooper, Ioannou, and Qi (2018)). Regarding experimental studies of Global Coordination games, we are aware only of the following three studies. Heinemann, Nagel, and Ockenfels (2004) study an experiment that resembles the speculative attack model of Morris and Shin (1998), but with repeated play. In comparing sessions between Common Knowledge and Global Coordination games, they find that subjects use threshold strategies in both informational protocols. In the Global games, they find that observed behavior is closer to the Global game solution. In their setup, the relevant economic fundamental is the profit from short selling the currency, which is drawn anew at the start of each repeated interaction.[3] In the Common Knowledge games, the authors find that observed behavior lies between the payoff-dominant equilibrium and the Global game solution.

Cabrales, Nagel, and Armenter (2007) study an experiment that resembles the 2×2 setup of Carlsson and van Damme (1993). Analogous to Heinemann, Nagel, and Ockenfels (2004), Cabrales, Nagel, and Armenter (2007) also investigate subjects' behavior in Common Knowledge and Global Coordination games, but distinguish between short-term and long-term play. The authors utilize a discrete state space with five possible states and signals to make the theoretic reasoning simpler. Cabrales, Nagel, and Armenter (2007) find that in the Global games with long-term play, subjects' behavior converges towards the Global game solution. The authors also find that in the Common Knowledge games with short-term play, observed behavior of

[3] The context of a subject's decision differs in our setup compared to the one in Heinemann, Nagel, and Ockenfels (2004). In our setup, a subject has to sacrifice an amount of money (pay a non-refundable fee) from the initial endowment to buy the cash amount. Otherwise, a subject gets to keep the endowed amount. In the study of Heinemann, Nagel, and Ockenfels (2004), subjects are required to decide between the safe and the risky action; however, the risky action does not take away any money from their total earnings.

subjects can be anywhere (weakly) between the payoff-dominant equilibrium and the Global game solution. Moreover, Cabrales, Nagel, and Armenter (2007) establish that subjects' behavior across the Common Knowledge and Global games with short-term play is statistically similar. This is a departure from the findings of Heinemann, Nagel, and Ockenfels (2004). According to Cabrales, Nagel, and Armenter (2007) (p. 232), the difference in results may be driven by the absence of learning effects.

Szkup and Trevino (2015) implement a different informational structure than the two previous studies. Specifically, the authors develop a two-stage model, where each agent, in the first stage, has the possibility to choose, at a cost, the precision of their private signal, and, in the second stage, play the Coordination game, as in Morris and Shin (1998), using the information acquired in the first stage. Szkup and Trevino (2015) prove existence of a unique equilibrium in their model. However, contrary to the theoretical predictions, they find that as subjects choose more precise information they coordinate more often on attacking the currency, and as a result attacks are more successful when agents hold more precise information.

3 Theoretical Predictions

We deploy the canonical Coordination game used in Morris and Shin (1998) (with different notation). Denote by N the number of players, who decide whether to register to buy the cash amount (referred to simply as "register" hereafter) or abstain from registering to buy the cash amount (referred to simply as "abstain" hereafter). Assume that indifferent players choose not to register. Denote by T the registration fee, Y the state of economic fundamentals, and $Y/2$ the cash amount gross of the fee with $Y \in \{Y_{min}, Y_{min}+1, ..., Y_{max}-1, Y_{max}\}$. Here, the state of economic fundamentals Y reflects profitability (i.e. the size of the cash amount). In particular, Y_{min} is the worst state in terms of profits, whereas Y_{max} is the most profitable state. The cash amount is awarded if the number of registered players is at least as high as $\alpha(Y)$. Therefore, after letting ν be the number of other players who register, and $r \in \{0, 1\}$ the player's decision to register ($r = 1$) or not, the payoff of each player is $r\Big(\mathbf{1}_{\{\nu \geq \alpha(Y)-1\}}\frac{Y}{2} - T\Big)$. The function $\alpha(.)$ and the registration fee are common knowledge. We set $\alpha(Y) = C - \frac{Y}{D}$ with $C > 0, D > 0$, and $C - \frac{Y_{max}}{D} \leq 1$. The last condition states that in the state Y_{max}, the cash amount is awarded even if only one player registers. Note that for $Y \geq \overline{Y} \equiv \alpha^{-1}(1)$, a single registration is enough for the cash amount to be awarded, while for $Y < \overline{Y}$ more than one registrations will typically be needed. We assume that $2T < \overline{Y}$ to ensure that it is not weakly dominant to abstain from registering when $Y < \overline{Y}$. Let $\underline{Y}$ be the largest of the economic fundamentals $2T$ and $\alpha^{-1}(N)$. It is dominant to abstain for any state $Y < \underline{Y}$. To ensure that this range of fundamentals is non-empty we assume $2T > Y_{min}$.

We distinguish between three cases regarding agents' information about economic fundamentals and the number of players. In the first case, there is common knowledge of economic fundamentals and the number of players. We refer to the corresponding strategic interaction as the Common Knowledge game. In this game, zero registrations (the maximin outcome) is the unique equilibrium outcome for $Y < \underline{Y}$.[4] Furthermore, N registrations (the payoff-dominant outcome) is the unique equilibrium for $Y \geq \overline{Y}$. However, in the "grey area" (i.e. in the remaining area of economic fundamentals) there is multiplicity of equilibria. Depending on self-fulfilling beliefs both the maximin and payoff-dominant outcomes (zero and N registrations, respectively) are equilibria.

The other two cases are captured by the Global and Poisson games. To facilitate their comparison with each other and with the Common Knowledge games, we note here that both Global (due to being Bayesian) games and Poisson games are subsumed by the general class of population uncertainty games, with each of them emerging from different informational structures.[5] In Global games, the number (and identity) of players in the game N is common knowledge and players receive private identically distributed and conditionally independent signals/hints about the unknown state of economic fundamentals Y. The set of signals is $\{x_{min}, x_{min}+1, ..., x_{max}-1, x_{max}\}$ and we denote a generic element of this with x or y. In the Poisson games, economic fundamentals are common knowledge, whereas it is commonly understood that the number of actual players in the game is a Poisson random variable with mean n. In Poisson games, the only signal players receive reveals to them whether they are active players in the game. Given the aforementioned framework, a natural question is: how

[4] If $\underline{Y} = 2T$, then registering when $Y = \underline{Y}$ is never profitable because even if enough registrations are made so that the cash amount is awarded, the latter just covers the registration fee. Therefore, it is weakly dominant to forego registering when $Y = \underline{Y} = 2T$.

[5] In general population uncertainty games, the number of players of each type is a random variable. When these are Poisson random variables, and the type set is singleton, the game reduces to a Poisson one. When the type set is not singleton, but the realizations that feature more than N players carry zero probability, the game reduces to a Bayesian one with N players. See Myerson (1998) for details.

does behavior change under the informational structures in the Global and Poisson games vis-a-vis the common knowledge environment? We answer this question by comparing the changes in subjects' behavior due to alternative elements of uncertainty by using as reference the behavior under common knowledge.

Consider first the Global games, where we suppress the dependence of various variables on the commonly known N to simplify notation. Denote the conditional probability distribution of the signal of a player with $\Pr(x|Y)$. Let also $\Pr(Y|y)$ be the posterior belief of a player with signal y over the state of economic fundamentals Y. We will say that a distribution f first-order stochastically dominates distribution f' if the cumulative of f is (weakly) lower than the cumulative of f'. We assume:

A1: $\Pr(\cdot|y')$ first-order stochastically dominates $\Pr(\cdot|y)$ for all $y' > y$.

A2: $\Pr(\cdot|Y')$ first-order stochastically dominates $\Pr(\cdot|Y)$ for all $Y' > Y$.

A1 says that the higher the received signal is, the more likely it is that the economic fundamentals are high. A2 says that the higher the state of economic fundamentals, the more likely it is that the signals received by the players are high.

From the point of view of a player with signal y who registers, the number of other players registering when all other players are expected to register if their signal is higher than x, and the economic fundamentals are Y, is a binomial random variable with size parameter $N-1$ and "success probability" $\sum_{\tilde{x}=x+1}^{x_{max}} \Pr(\tilde{x}|Y)$. Thus, the probability attached by a player with signal y who registers on the event that the threshold is met, when all other players are expected to register if their signal is higher than x, and the economic fundamentals are Y, is given by

$$G(Y,x) := \sum_{\tau=\lceil \alpha(Y) \rceil -1}^{N-1} \binom{N-1}{\tau} \Big(\sum_{\tilde{x}=x+1}^{x_{max}} \Pr(\tilde{x}|Y) \Big)^{\tau} \Big(1 - \sum_{\tilde{x}=x+1}^{x_{max}} \Pr(\tilde{x}|Y) \Big)^{N-1-\tau},$$

where the symbolic function $\lceil \cdot \rceil$ rounds-up the fraction to the nearest integer from above. Note that a binomial distribution with some parameters first-order stochastically dominates a binomial distribution with lower parameters. Given A2, we then have that $G(Y,x)$ is non-decreasing in Y, and non-increasing in x.

Let us now focus on a symmetric Bayesian Nash Equilibrium (BNE) where all players register if and only if their signal is higher than x^* (i.e. use a threshold strategy), with $x^* \in \mathbb{R}$. A symmetric BNE threshold signal x^* is such that

$$\sum_{Y=Y_{min}}^{Y_{max}} \Pr(Y|y) G(Y, x^*) Y/2 > T, \text{ if and only if } y > x^*. \tag{1}$$

The above condition expresses, in effect, that an expected utility maximizer will not take the bet if the expected profit is not higher than the price, where, here, taking the bet is identified with the act of registering, the price is identified with the fee and the expected profit with the left-hand side of the above inequality. Note that A1 and the aforementioned properties of G imply that the left-hand side of the inequality in (1) is non-decreasing in y and non-increasing in x^*, and so x^* may not be unique.

To characterize the threshold signals x^*, in our experiments, we assume that the posterior $\Pr(Y|y)$ is the uniform distribution over $\{y-\varepsilon_Y, y-\varepsilon_Y+1, ..., y+\varepsilon_Y-1, y+\varepsilon_Y\}$ and that $\Pr(x|Y)$ is the uniform distribution over $\{Y-\varepsilon_Y, Y-\varepsilon_Y+1, ..., Y+\varepsilon_Y-1, Y+\varepsilon_Y\}$ where $\varepsilon_Y := Y_{min} - x_{min} = x_{max} - Y_{max} > 0$. These satisfy assumptions A1 and A2, and so condition (1) is valid for our experiments. As we discuss in the next section, parameters are chosen to ensure uniqueness of the equilibrium outcome. This will be the case if the realized Y is such that $Y + \varepsilon_Y \leq x^*$ (and so no player registers), or such that $Y - \varepsilon_Y > x^*$ (and so all players register), for all x^* that satisfy (1).

We turn to the Poisson games. Let $F(\cdot \mid n)$ denote the Poisson cumulative distribution function with parameter n. It is straightforward to see that if $Y \leq 2T$, then it is never profitable to register. Moreover, if $Y \geq \overline{Y}$, then a single registration is enough for the cash amount to be awarded, and so every player finds it optimal to register. If $2T < Y < \overline{Y}$, then all players in the game abstaining is clearly an equilibrium regardless of the realized number of other players. If, however, the typical other player in the game registers with some strictly positive probability, then beliefs about the number of other players is important for decisions. According to the "environmental equivalence" property, shown in Myerson (1998), from the point of view of a player who has found himself in the game, the number of other players is a Poisson random variable with the mean number be equal to the mean number of players from the point of view of an outsider (or a potential player); that is n. It follows that if all other players in the game register, $F(\nu|n)$ is the probability from the point of view of a player in the game that there will be ν registrations from the other players in the game. Then, clearly, when

$$\Big[1 - F(\lceil \alpha(Y) \rceil - 2 \mid n)\Big] \frac{Y}{2} \leq T, \tag{2}$$

no player registering is the unique symmetric equilibrium.[6] Importantly, the calculations for the derivation of the the left-hand side of the inequality in (1) are more complex than those for the derivation of the left-hand side of the above inequality.

4 Experimental Design

Our experimental setup features a coordination problem that is examined under idiosyncratic uncertainty about economic fundamentals (i.e. a Global Coordination game) and Poisson population-size uncertainty (i.e. a Poisson Coordination game). As a baseline, we use a setup where economic fundamentals and number of players is common knowledge (i.e. a Common Knowledge Coordination game).

4.1 Design Choices

Before elaborating on the experimental procedures, we offer some clarifications with respect to our design choices. The experiments were conducted over the Internet. Internet is ideal for Poisson games as subjects cannot infer the number of participants, which is typically the case in a laboratory experiment. To maintain consistency with the Poisson treatments, the Global treatments and the controls based on Common Knowledge games were also conducted over the Internet. A disadvantage of running experiments over the Internet is that it becomes very hard to monitor participants' engagement with the game. In particular, there is no control over what participants are doing. For instance, participants could take a break to call someone, to browse the web, to eat pizza, to have a coffee etc. To safeguard against such distractions and to maintain subjects' focus to the game, the screens included timers that allowed a limited, but sufficient amount of time to read comfortably the instructions. In addition,

[6]As shown in Makris (2008), condition (2) ensures that no player registering is the unique equilibrium (in pure strategies), while if condition (2) is not satisfied then multiplicity of equilibria emerges.

the inclusion of timers minimized the possibility of wired or wireless communication. Once the time lapsed, the subjects would concurrently move to the next screen.[7]

The level of Y was drawn from the set of integers 5 to 95 according to the uniform distribution. For design reasons, the level of Y was drawn ahead of *all* experiments conducted. The drawn Y was 25. In Heinemann, Nagel, and Ockenfels (2004), there is a one-to-one map between the Y and the cash amount. However, a cash amount of £25 seems unreasonably high for an experiment lasting approximately 20 minutes. Instead, we decided to offer the cash amount of £$\frac{Y}{2}$ (i.e. £12.50). To ensure comparability across game types, the cash amount used in Common Knowledge and Poisson games was also set to £12.50.

Poisson and Global games have been proposed to address equilibrium indeterminacy in Common Knowledge Coordination games. Thus, suitable parameters should be chosen to satisfy the requirement of multiplicity in the Common Knowledge games and uniqueness of the equilibrium outcome in the Poisson and Global games. Specifically, parameters should be chosen such that the drawn Y lies within the "grey area" of $\underline{Y}$ and $\overline{Y}$, and the rest of the parameters satisfy condition (2) while ensuring that the symmetric BNE in threshold strategies of the Global games (recall (1)) imply the same behavior regardless of the realized signals to simplify the cognitive requirements for subjects. However, given that choosing parameters such that all players do register under symmetric BNE in threshold strategies of the Global games would imply multiplicity of equilibria in the corresponding Poisson games,[8] we chose parameters such that the prediction of the Global games prescribes, similar to Poisson games, that all players would not register irrespective of the realized signals.

Finally, we restricted our attention to single-shot experiments. In real life, for many applications of Coordination games, there are ample (personal or social) learning opportunities. Therefore, it would have been interesting to study the impact of

[7]In the questionnaire that followed the game-play stage, none of the subjects reported running out of time while reading the instructions on any of the screens.

[8]The way we have checked this is as follows. We asked, for given Y_{max} and Y_{min}, what are the values for N, C, D, T and ε_Y that satisfy the various constraints of the model and maximize the difference $Y^P - (x^G + \varepsilon_Y)$, where Y^P is the solution to condition (2) as an equality, and x^G is the highest symmetric BNE threshold signal. We have solved this optimization problem numerically by deploying the genetic algorithm in MATLAB (R2014b), with 'initial population' size of 2900 admissible profiles of control variables (N, C, D, T, ε_Y), and requiring that N and ε_Y are integers. We found that the value function of this problem is negative. This implies that the only states Y that would generate signals that are higher than any symmetric BNE threshold signal (i.e. $Y > x^G + \varepsilon_Y$) are higher than Y^P and thereby violate condition (2).

learning on subjects' behavior with iterative play. Despite our desire to investigate the three game types experimentally in a repeated setup, such task was deemed unfruitful. To see why, recall, first, that Global games put emphasis on uncertainty about economic fundamentals, and hence such uncertainty should be preserved when studying learning in repeated play. In other words, echoing also the approach in Heinemann, Nagel, and Ockenfels (2004), Y must be drawn anew at the start of each repeated interaction in Global, (and to maintain consistency in) Poisson and Common Knowledge games. Second, ensuring that the theoretical prediction prescribes that there is equilibrium indeterminacy in the Common Knowledge games, and in both the Poisson games and in the Global games no player registers, requires a fine tuning of the parameters in the three game types after each draw of Y. However, such parameter variability implies the strategic environment would change period after period unless the drawn Y was the same on consecutive draws.[9] It is thus very much questionable what could have been learned in such a tremendously-volatile environment within a few dozen iterations. Instead, we chose to focus on single-shot experiments to maintain the clarity of our conclusions.

4.2 Experiments

Upon logging in, subjects were endowed with £12 in lieu of a show-up fee. Subjects were then provided with the instructions. The instructions accommodated the underlying assumptions of the corresponding theories. Right after the delivery of the instructions, subjects were asked to make a decision on whether to buy the cash amount. Finally, subjects were asked to complete a short questionnaire consisting of demographic questions. With the conclusion of the experimental session, subjects claimed their earnings from the school office of Social Sciences at the University of Southampton.

First, we describe the Poisson treatments. In the first stage of the experiment, subjects were instructed that there would be a computer draw and that the number drawn would correspond to the number of subjects participating in the second stage of the experiment.[10] Subjects were explicitly told that the number drawn would not

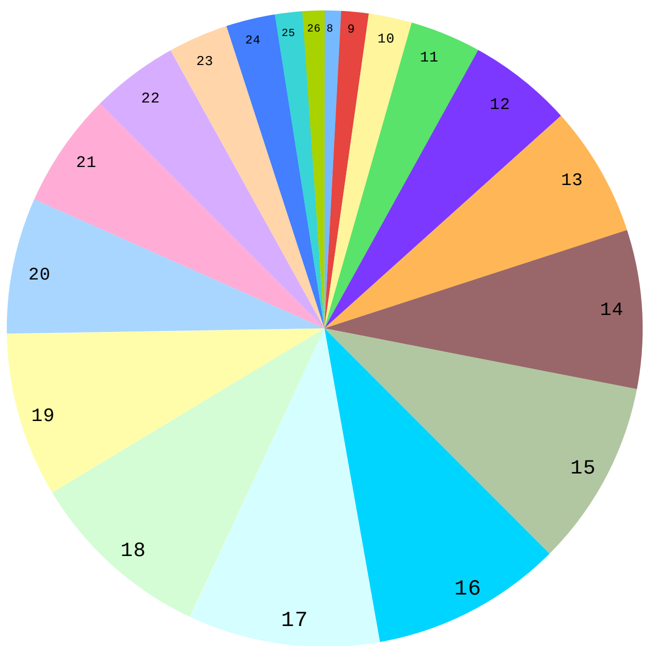
[9]The probability of hitting the same Y in two consecutive draws is around 1%.

[10]In each of the Poisson sessions, we sent log in information to 26 subjects. The total number of participants in each Poisson treatment is shown in Table 1.

be revealed to them. The Poisson process was based on $n = 17$. To circumvent the difficulties that would arise given the (assumed) unfamiliarity of many subjects with Poisson probabilities, we applied the specific probabilities onto a roulette wheel (see Figure 1). We showed the roulette wheel pictorially and noted the following.

> You can see that the roulette is not a standard roulette; the number drawn can be any number between 8 and 26, but not all numbers are equally likely to be drawn. Numbers closer to 17 (the mean) are more likely to be drawn.[11]

Figure 1: Roulette Wheel in the Poisson Treatments for $n = 17$



Notes: We circumvented the difficulties that would arise given the (assumed) unfamiliarity of many subjects with Poisson probabilities by applying the specific probabilities onto a roulette wheel.

The instructions specified that subjects not selected to participate in the second stage of the experiment would be dismissed, but would keep their initial endowment.

In the second stage, subjects had the option to buy the cash amount of £12.50 at a fee of £9 (£10). Subjects were informed that the cash amount of £12.50 would be issued only if a minimum of 16 (15) subjects registered to buy it, and that the fee

[11]We restricted the roulette wheel to values up to and inclusive of 26. Above 26, the probability drops to below 0.007; that is, it is nearly zero.

of £9 (£10) required for the purchase was non-refundable and collected immediately. That is, if a subject registered, the £9 (£10) would be subtracted automatically from the initial endowment regardless of the number of subjects registering. The subjects were then asked to indicate whether they would like to register.

Analogous to the Poisson treatments, Global treatments also included a computer draw in the first stage. The drawn integer (between 5 and 95 inclusive) was referred to as "Y" in the instructions. We forewent indicating the actual Y drawn, yet we provided subjects with a *hint* about the drawn Y. The hint was an integer within a range of $+5$ and -5 from the Y drawn.[12] For example, for $Y = 25$, subjects would receive a hint integer in the set of $\{20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30\}$, where each integer had a probability of $\frac{1}{11}$ of being drawn. The hint integer was indicated in bold. Additionally, the number of subjects participating in the experiment was set at $N = 17$ and was indicated on the screens.

In the second stage of the experiment, subjects had the option to buy the cash amount of £$\frac{Y}{2}$ at a non-refundable fee of £9 (£10). The cash amount would be awarded conditional on at least $\alpha(Y) = C - \frac{Y}{4}$ registering to buy it, where C was replaced in the experimental instructions by 22 (21) when the fee was £9 (£10). In order to circumvent calculation errors, we indicated on the screen the number of subjects that needed to register to win the cash amount for every possible value of Y.[13] The subjects had to indicate next whether they would like to register.

In the Common Knowledge controls, subjects were told the number of participants (i.e. 17), the cash amount (i.e. £12.50), the fee (i.e. £9 or £10) and the threshold number of registrations (i.e. 16 or 15) to earn the cash amount. The subjects were then asked to make a decision, analogous to the Poisson and Global treatments.

The experimental sessions took place in October of 2013, May of 2014, and December of 2017. We conducted two sessions per treatment. The 220 subjects were recruited from the undergraduate student population of the University of Southamp-

[12] To map the values here to the notation in Section 3, let $Y_{max} = 95$, $Y_{min} = 5$, $\varepsilon_Y = 5$ and thereby $x \in [0, 100]$.

[13] Recall that in the Global games the number of participants is common knowledge. For some values of Y (e.g. $Y = 18$), more participants are required to register for the cash amount to be awarded than the ones commonly known to be present. We conducted sessions where the additional intervals for implausible realizations of the cash amount are excluded from the experimental instructions and sessions where these additional intervals are included. The results are almost identical. However, for the purpose of maintaining consistency between the theory and the games in the experiments, we chose to include in the analysis only the sessions where the additional intervals are included.

ton. We announced our experiments via class presentations. In order to participate, students replied by e-mail. We then indicated to the respondents the date and time of the experiment, and asked them to confirm their attendance. Those who confirmed were subsequently sent log in information (username and password) and the url of the website. Most of the participants majored in business, economics, finance, and mathematics. Participants were allowed to participate in *only* one session. Average earnings per participant were £9.01. Specifically, in the Common Knowledge games, subjects made on average £7.24, in the Poisson games, subjects made on average £11.55, whereas in the Global games, the average earnings were £7.66. The experimental instructions are reported in the Appendix. Some general characteristics of the sessions are shown in Table 1. Note that each experiment is denoted by an acronym. In particular, the acronym $(type, threshold, fee)$ consists of the *type* of game (*CK* for Common Knowledge games or *P* for Poisson games or *G* for Global games), the *threshold* (15 or 16) and the *fee* (9 or 10).

4.3 Parameter Choices

We justify next our parameter choices. Recall that the drawn Y was 25 and the cash amount was $\pounds\frac{Y}{2}$ (i.e. $\pounds 12.50$). The number of players in the games had to be relatively large to capture the "largeness" of the games while being cost effective. This motivates our choice of the number of players ($N = 17$) in Global and Common Knowledge games. To ensure comparability across game types, the population mean of the Poisson distribution used in Poisson games (i.e. $n = 17$) had to also be equal to the number of players in Global and Common Knowledge games.

The threshold and the fee were chosen next. Presumably, a lower fee and a lower threshold would make subjects more willing to register to buy the cash amount. However, ensuring equilibrium uniqueness in the Poison games implies that we cannot choose low values for *both* the fee and the threshold number (recall condition (2)). In addition, the threshold number of registrations should not exceed the number of players in Common Knowledge games (otherwise, subjects would have a dominant strategy to forego registering). Our chosen parameters struck a balance when faced with a tradeoff between low fees and high threshold numbers at the design stage. To see this, observe the Poisson Cumulative Distribution Table (included in the Appendix) for $n = 17$, and fix the cash amount at $\pounds 12.50$. Consider the lowest fee

Table 1: Characteristics of the Experimental Sessions

Common Knowledge Games						
# of Subj.	# of Ses.	Mean	Threshold	Fee (£)	Amount (£)	Acronym
34	2	-	16	9	12.50	CK169
34	2	-	15	10	12.50	CK1510
Poisson Games						
# of Subj.	# of Ses.	Mean	Threshold	Fee (£)	Amount (£)	Acronym
40	2	17	16	9	12.50	P169
44	2	17	15	10	12.50	P1510
Global Games						
# of Subj.	# of Ses.	Mean	Threshold	Fee (£)	Amount (£)	Acronym
34	2	-	$22 - \lceil \frac{Y}{4} \rceil = 16$	9	$\frac{Y}{2} = 12.50$	G169
34	2	-	$21 - \lceil \frac{Y}{4} \rceil = 15$	10	$\frac{Y}{2} = 12.50$	G1510

Notes: In the first column, we provide the total number of participants in each experiment. We conducted two sessions per game type. The number of participants in the Global and Common Knowledge sessions was common knowledge. Notice that the number of participants in *each* session in the Global treatments and Common Knowledge controls coincides with the mean n of the Poisson treatments. Moreover, the cash amount is the same in the three game types. Also, in the calculation of the threshold in Global games, the symbolic function $\lceil \cdot \rceil$ rounds-up the fraction to the nearest integer from above. The acronyms in the last column consist of the game type (*CK* for Common Knowledge games or *P* for Poisson games or *G* for Global games), the threshold (15 or 16) and the fee (9 or 10).

required for the threshold number of registrations to be equal to the mean number of the Poisson distribution while satisfying condition (2). Looking at the table and applying condition (2) this fee is £7.86 (i.e. $(1 - 0.3715)12.5 < 7.86$). Having a threshold level which is equal to the mean number of the Poisson distribution could make subjects perceive it as less likely that the cash amount will be awarded. This in turn could make subjects unwilling to register. To make it harder for the theoretical prediction of the Poisson games to be confirmed by subjects' behavior, we showed preference towards increasing the fee by merely £1.14 and £2.14 in order to decrease the threshold number of registrations by 1 and 2 subjects (i.e. to 16 and 15), respectively. Similarly, lower threshold numbers, such as 11 would imply a fee significantly close to the cash amount. For example, the fee required for a threshold number of registrations of 11 is £12.18. It is therefore highly doubtful that a subject would risk losing the fee of £12.18 to earn the cash amount of £12.50. Instead, we chose to set the fee at £9 and £10 and thereby to set a threshold number of registrations of 16 and 15, respectively to ensure condition (2), while also ensuring that (a) the fee is not very close to the awarded cash amount, and (b) the threshold number of registrations is less than the mean number of the Poisson distribution. It is important to notice that trying to give the *worst* chance to Poisson games in the lab, we chose parameters to *barely* satisfy condition (2).

Considering the duration of the experiment (approximately 20 minutes) and the minimum wage in UK ($\approx$ £6 per hour), we stipulated that no subject should get a compensation below £2. Therefore, the difference between the highest fee (i.e. £10) and the endowment should not be less than £2, which led us to provide subjects with an initial endowment of £12.

4.4 General Hypotheses

We formulate next three hypotheses. The first and second hypotheses examine the behavioral differences across the treatments and the control. This is important in order to understand whether the types of uncertainty we focus on may influence strategic behavior in environments with strategic complementarities. Thus, we test for differences in subjects' behavior across Common Knowledge and Poisson games, and Common Knowledge and Global games.

Hypothesis 1 Subjects' behavior is statistically similar across the Common Knowledge and Poisson games when controlling for the parameter choices of each pairwise comparison.

Hypothesis 2 Subjects' behavior is statistically similar across the Common Knowledge and Global games when controlling for the parameter choices of each pairwise comparison.

Finally, the last hypothesis serves as a test of the theoretical predictions of the Poisson and Global games. Recall that the Poisson and Global games for the parameters specified, predict that *no* subject will register. However, we know already from plenty of experiments that subjects cannot perfectly coordinate in single-shot Coordination games. A single subject choosing to register is a sufficient datapoint to provide evidence against the theoretical prediction as the latter puts all probability on just one realization of total registrations (i.e. zero registations to buy the cash amount). Therefore, our formulated hypothesis is slightly forgiving in the sense that it allows for small behavioral errors (e.g. due to short attention spans, random distractions etc.) while at the same time ordering the proximity (defined precisely in Subsection 5.3) of one treatment over the other to the theoretical prediction.

Hypothesis 3 Subjects' behavior in the Poisson games is closer (defined precisely in Subsection 5.3) to the respective theoretical prediction relative to subjects' behavior in the Global games, for the parameters specified.

5 Results

Each hypothesis is matched with the corresponding result; that is, result i is a report on the test of hypothesis i. Note that the decision of a subject in the game is a binary variable. The subjects who chose not to register to buy the cash amount were assigned a value of 0. The subjects who chose to register were assigned a value of 1.

5.1 Summary Statistics

Table 2 reports descriptive statistics on the raw data. Recall that subjects had to decide whether to register to buy the cash amount at a fee or forego this option and keep the endowment of £12. In the table, we display the frequency and percentage of subjects who registered, and the frequency and percentage of subjects who did not register. With the exception of CK1510, in all other experiments, the subjects who chose not to register outnumbered the ones that chose to register. In the Common Knowledge and Global experiments, the percentages of those who kept the endowment of £12 range from 47.1% to 55.9%. In sharp contrast, the percentages in the Poisson treatments are substantially higher (95.0% in P169 and 95.5% in P1510). Overall, out of 220 subjects, 69 chose to register and 151 subjects chose not to register. The threshold was not met in any of the sessions; consequently, the cash amount was not awarded.

Table 2: Descriptive Statistics

Common Knowledge Games					
	Registered		Not Registered		Amount
Acronym	Freq.	%	Freq.	%	Awarded?
CK169	16	47.1	18	52.9	No
CK1510	18	52.9	16	47.1	No
Poisson Games					
	Registered		Not Registered		Amount
Acronym	Freq.	%	Freq.	%	Awarded?
P169	2	5.0	38	95.0	No
P1510	2	4.6	42	95.5	No
Global Games					
	Registered		Not Registered		Amount
Acronym	Freq.	%	Freq.	%	Awarded?
G169	15	44.1	19	55.9	No
G1510	16	47.1	18	52.9	No
Total	69		151		

Notes: The table indicates the number of subjects who registered, and the number of those who did not register in each experiment. In addition, we provide the corresponding percentages. The threshold was not met in any of the sessions. The acronyms consist of the game type (*CK* for Common Knowledge games or *P* for Poisson games or *G* for Global games), the threshold (15 or 16) and the fee (9 or 10).

In Table 3, we display the behavior of subjects in the two Global treatments conditional on the signal received. Recall that in the experiments, Y was set at 25, and subjects could receive signals in the range of $\{20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30\}$, where each signal had a probability of $\frac{1}{11}$ of being drawn. Recall further that the theoretical prediction is that no subject should register irrespective of the signal received.

Table 3: Decisions Conditional on Signals

	G169		*G1510*	
Signals	Registered Freq.	Not Registered Freq.	Registered Freq.	Not Registered Freq.
20	4	0	2	2
21	0	4	3	1
22	0	2	0	2
23	4	0	3	1
24	2	2	1	3
25	1	5	0	6
26	1	1	0	2
27	2	2	4	0
28	1	1	1	1
29	0	2	2	0
30	-	-	-	-

Notes: The table indicates the number of subjects who registered, and the number of those who did not register in the two Global treatments conditional on the signal received. The distribution of signals is identical across the two sessions and the two treatments.

5.2 Subjects' Behavior Across Game Types

Next, we investigate whether subjects' decisions varied significantly across the baseline Common Knowledge games and the Poisson and Global treatments, when the latter two game types predict a unique equilibrium. The hypotheses are formally tested through pairwise χ^2-tests, where the H_0 states that behavior across the pairwise comparisons is not statistically different. The results are displayed in Table 4 and formalized in our first and second results.[14]

Result 1 Subjects' behavior differs significantly between the Common Knowledge and Poisson games when controlling for the parameter choices of each pairwise comparison.

[14]We also conducted non-parametric Mann-Whitney tests and though the p-values only in the last two comparisons change slightly, the conclusions stay the same.

Result 2 Subjects' behavior does not differ significantly between the Common Knowledge and Global games when controlling for the parameter choices of each pairwise comparison.

Table 4: Differences in Subjects' Behavior Across Game Types

Alternative hypothesis:	$decision_i \neq decision_j$
	p-values
Common Knowledge games vs Poisson games	
CK169 & P169	0.000
CK1510 & P1510	0.000
Common Knowledge games vs Global games	
CK169 & G169	0.808
CK1510 & G1510	0.628

Notes: We utilize the χ^2-test to determine whether subjects' decisions differ across game types ($i \neq j$) conditional on the same parameters. The acronyms consist of the game type (*CK* for Common Knowledge games or *P* for Poisson games or *G* for Global games), the threshold (15 or 16) and the fee (9 or 10).

5.3 Theory and Subjects' Behavior

Poisson and Global games predict, for the parameters specified, that *no* subject will register. In our quest to investigate whether subjects' behavior in the Poisson and Global treatments is consistent with the theoretical prediction, we hit a big obstacle in that standard statistical hypothesis tests cannot be used on this occasion as a single subject choosing to register is a sufficient datapoint to provide evidence against the theoretical prediction. As we indicated in Subsection 4.4, existing experimental literature in single-shot Coordination games indicates that it is extremely unlikely that all subjects will perfectly coordinate on one outcome. To address this, we develop a procedure to investigate whether behavior in the lab is *close* (in a sense defined shortly) to the theoretical predictions. The key in this procedure is to allow for small behavioral errors that might arise due to short attention spans, random distractions etc. Crucially, the procedure we develop may also be useful for other *Binary games* (i.e. games where players choose one of two actions and an equilibrium is of the form that all players take the same action).[15]

5.3.1 A Statistical Procedure for Assessing the Closeness of Empirical and Theoretical Distributions in Binary Games

As already mentioned, we postulate that behavior in the lab may be influenced by "behavioral errors." The behavioral error is an iid random variable, which captures the probability with which the typical subject will take - for reasons "outside the theoretical model" - an action that is not predicted by the use of game-theoretic arguments in the Binary game under scrutiny. We thus postulate that the total number of registrations is a random variable $Z \sim Bin(N, \pi)$, where $Bin(N, \pi)$ is the binomial distribution with size parameter N (the number of independent trials/players) and "success probability" π. The key assumption here is that $\pi \sim Beta(a, b)$ for some exogenously given scalars $a \geq 1, b > 1$, where $Beta(a, b)$ is the Beta distribution with parameters a, b.[16] We note that the mean error is $\frac{a}{a+b}$ and that the case where subjects make an error with an infinitesimal probability (thus approximating the game-theoretic prediction) is captured by $\frac{a}{a+b} \to 0$.

To investigate whether behavior in the lab is "close" to the game-theoretic prediction of a total of zero registrations, and get a sense of how close it is, we will examine whether behavior in the lab is consistent with the H_0 that $Z \sim Bin(N, \pi)$ with $\pi \sim Beta(a, b)$ for predetermined values of a and b, paying particular attention to determining the set of values of (a, b) for which the H_0 is rejected. The latter is particularly useful in our case because we want to compare how close the empirical distribution to the theoretical prediction is of alternative treatments for the same Binary game. Thus, one could simply compare the sets of values of (a, b) for which the H_0 is rejected in the treatments under scrutiny.

[15]We are indebted to Valentin Patilea and Anastasios Magdalinos for invaluable discussions and guidance in developing this procedure.

[16]Conveniently, the distribution $Beta(\cdot, \cdot)$ is defined on the interval $[0, 1]$, hence can be used to describe the distribution of a probability value. The restrictions here on a and b are present *only* to capture our interpretation of π as an error which is likely to be small. They thus assume away cases where its pdf is strictly increasing (the case of $b = 1$) or is not uni-modal (the case of $a, b < 1$).

To summarise behavior in the lab and conduct our statistical procedure, we will use the total number of observed registrations Z as our statistic. We therefore need to derive the probability distribution of our statistic Z under the above H_0. It is shown in the Appendix that the probability distribution of our statistic Z under the above H_0 is $Bin(N, \frac{a}{a+b})$. Denoting with $p(z, \frac{a}{a+b})$ the p-value that corresponds to the realization z of the statistic Z, it follows that the H_0 is rejected given a realization z of the statistic and a level of significance $\alpha \in (0, 1)$ if

$$p(z; \frac{a}{a+b}) := \sum_{j=z}^{N} \binom{N}{j} (\frac{a}{a+b})^j (\frac{b}{a+b})^{N-j} < \alpha. \tag{3}$$

We know that $p(0; \pi) = 1$ for all $\pi \in [0, 1]$. We thus have that the H_0 cannot be rejected following a realization $z = 0$ of the statistic for any mean error $\frac{a}{a+b}$. Turning to the case of a realization $z > 0$ of the statistic, the level of the mean error plays a key role in rejecting or not the H_0. However, the actual choice of the mean error here is arbitrary in the absence of any additional information about subjects' behavior. Motivated by this, we now ask the alternative question of *how big is the range of values of the mean error for which a given realization $z > 0$ of the statistic would lead to a rejection of the H_0.* We know that $p(z; \pi)$ is increasing in π for all $z \in \{1, ..., N\}$, with $p(z; 1) = 1$ and $p(z; 0) = 0$. Therefore, there is a critical threshold for the mean error below which the H_0 is rejected, whereas for all (weakly) higher mean errors the H_0 is not rejected. This threshold mean, denoted hereafter by $\underline{\pi}(z)$ is in $(0, 1)$ and given implicitly by

$$\sum_{j=z}^{N} \binom{N}{j} (\underline{\pi}(z))^j (1 - \underline{\pi}(z))^{N-j} = \alpha. \tag{4}$$

Obviously, this threshold mean depends also on N and α, but we suppress this dependence (whenever there is no risk of confusion) for notational simplicity. This threshold summarizes naturally how "close" to the game-theoretic prediction behavior in the lab is; specifically, the lower the threshold mean error, the closer it is, because the interval of mean errors for which the H_0 is rejected (for a given realization $z > 0$) is smaller.

Note now that $p(z, \pi)$ is decreasing in z for all $\pi \in (0, 1)$. Consequently, we also have that $\underline{\pi}(z)$ is increasing in z. It follows that the smaller the realization $z > 0$ of the statistic, the closer the observed behavior is to the game-theoretic prediction.

Therefore, if one wishes to compare the empirical distributions of two alternative treatments (that both predict a total of zero registrations in the equilibrium), while keeping N and α the same across treatments, then one could argue that the theory that is "closer" to the observed behavior is the one with the *lower* realization of the statistic; this is because, the lower the realization of the statistic, the "less often" the above H_0 will be rejected. Next, we use this "characterization" of how close behavior in the lab is to the game-theoretic prediction - as summarised by the realization of our statistic - to compare alternative theories regarding their performance in the lab.

5.3.2 Threshold Mean Errors

The threshold mean errors for the Poisson and Global experiments are displayed in Table 5 when fixing the level of statistical significance at 1% and 5%, respectively. Therefore, keeping N and α the same in the pairwise comparisons, we can argue that subjects' behavior in the Poisson experiments is "closer" to the respective theoretical prediction relative to subjects' behavior in the Global experiments because the statistic is lower in the Poisson experiments. This result implies that the Global game may be associated with a higher mean error than the Poisson game. One possible explanation of this might be that, as we have already hinted in Section 3, the calculations needed in the Global game are more demanding than those in the Poisson game. We formalize next our third result.

Result 3 Fixing the level of statistical significance, subjects' behavior in the Poisson games is closer to the respective theoretical prediction relative to subjects' behavior in the Global games, for the parameters specified.

5.3.3 Marginal Effects

Given that our sample size is large enough, we also run a probit regression where the dependent variable is a subject's decision and the four treatments and two controls are the covariates with CK169 set as the base. Acknowledging that coefficients in probit models are up to scale and cannot be directly interpreted, we only present the marginal effects in Table 6. The standard errors are reported in parentheses. Crucially, the coefficients are statistically significant only in the Poisson games. The

Table 5: THRESHOLD MEAN ERRORS

Level of statistical significance is set at 1%	
G169	0.246
G1510	0.271
P169	0.004
P1510	0.003
Level of statistical significance is set at 5%	
G169	0.295
G1510	0.322
P169	0.009
P1510	0.008

Notes: We utilize the statistical procedure we developed for Binary games. Our H_0 states that $Z \sim Bin(N, \pi)$ with $\pi \sim Beta(a, b)$ for predetermined values of $a \geq 1, b > 1$. Fixing the level of statistical significance, the lower the statistic, the "less often" the H_0 will be rejected. The acronyms consist of the game type (P for Poisson games or G for Global games), the threshold (15 or 16) and the fee (9 or 10).

marginal effects imply a decrease in probability of 42.1% (P169) and 42.5% (P1510) in registering to buy the cash amount in the Poisson treatments.

6 Robustness Analysis

Contrasting the behavior in the Common Knowledge and Poisson games for parameters where Poisson games predict a unique equilibrium while Common Knowledge games predict multiplicity of equilibria, we found that subjects' behavior across the two game types is statistically different. This result suggests that uncertainty regarding the number of actual players may influence subjects' behavior. Specifically, in the Common Knowledge games, we found that subjects split almost evenly between not registering and registering. However, in the Poisson games, almost all subjects

Table 6: MARGINAL EFFECTS

Dependent variable:	decision
Regressor	dy/dx
CK1510	0.059
	(0.121)
P169	-0.421***
	(0.092)
P1510	-0.425***
	(0.091)
G169	-0.029
	(0.121)
G1510	0.000
	(0.121)
Number of obs	220

Notes: We report marginal effects after a probit regression on decision. CK169 is set as the base against which the estimated parameters are compared. dy/dx for factor levels is the discrete change from the base level. All standard errors are reported in parentheses. The acronyms consist of the game type (*CK* for Common Knowledge games or *P* for Poisson games or *G* for Global games), the threshold (15 or 16) and the fee (9 or 10). *** Significant at the 1% level.

did not register. Crucially, such behavior in the Poisson games is close to the respective theoretical prediction. Both results are important findings that deserve further scrutiny. We thus conducted a number of robustness sessions with smaller and larger sample sizes. The characteristics of the robustness sessions are displayed in Table 7, and their corresponding experimental instructions are included in the Appendix.

First, we investigated subjects' behavior with a smaller sample size. We ran four, Common Knowledge sessions and four, Poisson sessions. In the Common Knowledge games, four subjects participated in each session. The choice of a setup with four subjects was motivated by the extensive literature in the Turnaround games (Brandts and Cooper (2006), Brandts, Cooper, and Fatas (2007) and Cooper, Ioannou, and Qi (2018)). Consequently, given the choice of $N = 4$, to ensure comparability between the Common Knowledge and Poisson games, we set the mean of the Poisson distribution to $n = 4$. Moreover, in both game types, the threshold was set to $\alpha(Y) = 4$. This choice was made for two reasons. First, having a setup where the threshold exceeds

Table 7: Characteristics of Robustness Sessions

Common Knowledge Games						
# of Subj.	# of Ses.	Mean	Threshold	Fee (£)	Amount (£)	Acronym
16	4	-	4	10	12.50	SCK410
38	2	-	18	9	12.50	LCK189
38	2	-	17	10	12.50	LCK1710
Poisson Games						
# of Subj.	# of Ses.	Mean	Threshold	Fee (£)	Amount (£)	Acronym
16	4	4	4	10	12.50	SP410
48	2	19	18	9	12.50	LP189
46	2	19	17	10	12.50	LP1710

Notes: In the first column, we provide the total number of participants in each experiment. For each game type, we conducted four sessions in the small sample experiments and two sessions in each of the large sample experiments. The number of participants in the Common Knowledge sessions was common knowledge. Note that the number of participants in *each* session in the Common Knowledge games coincides with the mean n of the Poisson games. This was done to ensure comparability across the two game types. The acronyms consist of the magnitude of the sample size (S for small sample size or L for large sample size), game type (CK for Common Knowledge games or P for Poisson games), the threshold (4 or 17 or 18) and the fee (9 or 10).

the (expected) number of players is problematic because (a) such setup would invite experimenter effects, and (b) it would be dominant for subjects to not register in Common Knowledge games. Second, the only value for the threshold level that does not exceed the mean population and ensures equilibrium uniqueness in the Poisson games is in fact $\alpha(Y) = 4$ for the parameters specified (i.e. $n = 4$, $\frac{Y}{2} = \pounds 12.50$, $T \in \{9, 10\}$). Next, we experimented with a larger sample size. Our choice was to set $N = 19$ in the Common Knowledge games and $n = 19$ as the mean of the Poisson distribution in the Poisson games. For the larger group size, we decided to run two experiments in an analogous manner to the earlier ones. The fee was set at either $T = \pounds 9$ or $T = \pounds 10$, which corresponds to a threshold number of 18 and 17, respectively. These choices ensured equilibrium uniqueness in the Poisson games in a similar manner to our corresponding parameter choices under the smaller sample sizes.

Table 8: Descriptive Statistics of Smaller & Larger Sample Sizes

Common Knowledge Games					
	Registered		Not Registered		Amount
Acronym	Freq.	%	Freq.	%	Awarded?
SCK410	7	43.8	9	56.3	No
LCK189	16	42.1	22	57.9	No
LCK1710	18	47.4	20	52.6	No
Poisson Games					
	Registered		Not Registered		Amount
Acronym	Freq.	%	Freq.	%	Awarded?
SP410	1	6.3	15	93.8	No
LP189	3	6.3	45	93.8	No
LP1710	2	4.4	44	95.7	No

Notes: The table indicates the number of subjects who registered, and the number of those who did not register in each experiment. In addition, we provide the corresponding percentages. The threshold was not met in any of the sessions. The acronyms consist of the magnitude of the sample size (S for small sample size or L for large sample size), game type (CK for Common Knowledge games or P for Poisson games), the threshold (4 or 17 or 18) and the fee (9 or 10).

Table 8 reports descriptive statistics on the raw experimental data of smaller and larger sample sizes. Similar to the earlier findings, the threshold was not met in any of the sessions; consequently, the cash amount was not awarded. Furthermore, in the Common Knowledge games, the number of subjects is split between those choosing to register and those choosing not to register, whereas, in the Poisson games, only 6 subjects out of the 110 that participated registered. The other 104 subjects did not register.

In Table 9, we present the robustness analysis for the smaller sample size. For the analysis, we utilize Fisher's exact test. Panel A calculates the p-value to determine whether subjects' decisions differ across the Common Knowledge and Poisson games conditional on the same parameters. The H_0 states that behavior between the two game types is not statistically different. The p-value in the pairwise comparison is be-

Table 9: Robustness Analysis for Small Samples

Panel A	
Alternative hypothesis:	$decision_i \neq decision_j$
	p-value
Common Knowledge games vs Poisson games	
SCK410 & SP410	0.019
Panel B	
	Threshold mean error
Level of statistical significance is set at 1%	
SP410	0.001

Notes: The decision of a subject in the game is a binary variable. The subjects who chose not to register were assigned a value of 0; otherwise, were assigned a value of 1. For the analysis, we utilize Fisher's exact test. Panel A calculates the p-value under the H_0 that behavior across the Common Knowledge and Poisson games ($i \neq j$) is not statistically different conditional on the same parameters. Panel B indicates the threshold mean error below which the H_0 that $Z \sim Bin(N, \pi)$ with $\pi \sim Beta(a, b)$ for predetermined values of $a \geq 1, b > 1$ is rejected when the level of statistical significance is 0.01. The acronyms consist of the magnitude of the sample size (S for small sample size), game type (CK for Common Knowledge games or P for Poisson games), the threshold (4) and the fee (10).

low the 2% level of statistical significance. Therefore, the H_0 is rejected. Furthermore, Panel B displays the threshold mean error below which the H_0 that $Z \sim Bin(N, \pi)$ with $\pi \sim Beta(a, b)$ for predetermined values of $a \geq 1, b > 1$ is rejected when the level of statistical significance is 0.01.

Table 10 presents the robustness analysis for the larger sample size. In particular, Panel A tests whether subjects' decisions varied significantly across the Common Knowledge and Poisson games when controlling for the parameter choices. We find that subjects' behavior differs significantly between the two game types. All the p-values in the pairwise comparisons are below the 1% level of statistical significance. Panel B indicates the threshold mean error below which the H_0 that $Z \sim Bin(N, \pi)$ with $\pi \sim Beta(a, b)$ for predetermined values of $a \geq 1, b > 1$ is rejected when the level of statistical significance is 0.01. Finally, in Panel C, we take advantage of the large sample size to present the marginal effects. LCK189 is set as the base. The standard

Table 10: Robustness Analysis for Large Samples

Panel A	
Alternative hypothesis:	$decision_i \neq decision_j$
	p-values
Common Knowledge games vs Poisson games	
LCK189 & LP189	0.000
LCK1710 & LP1710	0.000
Panel B	
	Threshold mean error
Level of statistical significance is set at 1%	
LP189	0.009
LP1710	0.003
Panel C	
Dependent variable:	decision
Regressor	dy/dx
LP189	-0.359***
	(0.087)
LP1710	-0.378***
	(0.086)

Notes: The decision of a subject in the game is a binary variable. The subjects who chose not to register were assigned a value of 0; otherwise, were assigned a value of 1. In Panel A, we utilize the χ^2-test to determine whether subjects' decisions differ across the Common Knowledge and Poisson games ($i \neq j$) conditional on the same parameters. In addition, Panel B indicates the threshold mean error below which the H_0 that $Z \sim Bin(N, \pi)$ with $\pi \sim Beta(a, b)$ for predetermined values of $a \geq 1, b > 1$ is rejected when the level of statistical significance is 0.01. In Panel C, we report marginal effects after a probit regression on decision. LCK189 is set as the base against which the estimated parameters are compared. dy/dx for factor levels is the discrete change from the base level. All standard errors are reported in parentheses. The acronyms consist of the magnitude of the sample size (L for large sample size), game type (CK for Common Knowledge games or P for Poisson games), the threshold (17 or 18) and the fee (9 or 10). *** Significant at the 1% level.

errors are reported in parentheses. The coefficients are statistically significant in the Poisson games. More specifically, the marginal effects imply a decrease in probability of 35.9% in LP189 and 37.8% in LP1710 in registering in the Poisson treatments.[17]

7 Discussion

Our findings suggest that uncertainty about the number of actual players has a more significant impact on subjects' behavior than idiosyncratic uncertainty about economic fundamentals, when these two types of uncertainty lead to a prediction of a unique equilibrium. Furthermore, our statistical test highlights that subjects' behavior under Poisson population-size uncertainty is closer to the respective theoretical prediction than subjects' behavior in the Global games. However, a number of natural questions still remain unanswered. How does subjects' behavior change as we increase (or decrease) the threshold level? Is population uncertainty an inherent deterrent of registrations such that under no circumstances will subjects register? Why is there such a large observed difference in the number of subjects choosing to forego registering across the Poisson and Global treatments? These questions are addressed in turn in what follows.

7.1 Comparative Statics

We first conducted a comparative statics exercise to shed light on the interplay between subjects' behavior and Poisson population-size uncertainty. Specifically, we varied the threshold in order to observe its impact on the empirical distribution of registrations in a Poisson experiment when the fee is £9, the cash amount is £12.50 and the mean number of the Poisson distribution n is 17.[18] As controls, we conducted analogous Common Knowledge experiments where we also varied the threshold level while keeping fixed the fee at £9, the cash amount at £12.50 and the number of

[17]We also ran marginal effects with LCK1710 set as the base. With the latter base, the marginal effects imply a decrease in probability in the Poisson treatments of 41.1% in LP189 and 43.0% in LP1710 in registering. Both results are statistically significant at the 1% level.

[18]In principle, we could have varied instead the mean of the Poisson distribution, or the fee, or even the cash amount. We showed preference towards changing the threshold simply because it led to the least number of changes in the experimental instructions. For one, changing the mean of the distribution would lead to different roulette wheels and for another, changing the fee or the cash amount would lead to further changes in the final payoffs provided.

participants at 17. Some general characteristics of the comparative statics sessions are shown in Table 11. In Table 12, we report the corresponding descriptive statistics on the raw data.[19]

Table 11: CHARACTERISTICS OF THE COMPARATIVE STATICS SESSIONS

# of Subj.	# of Ses.	Mean	Threshold	Fee (£)	Amount (£)	Acronym
Common Knowledge Games						
17	1	-	13	9	12.50	CK139
17	1	-	14	9	12.50	CK149
17	1	-	15	9	12.50	CK159
17	2	-	16	9	12.50	CK169
17	1	-	17	9	12.50	CK179
17	1	-	18	9	12.50	CK189
Poisson Games						
# of Subj.	# of Ses.	Mean	Threshold	Fee (£)	Amount (£)	Acronym
21	1	17	13	9	12.50	P139
14	1	17	14	9	12.50	P149
16	1	17	15	9	12.50	P159
40	2	17	16	9	12.50	P169
23	1	17	17	9	12.50	P179
15	1	17	18	9	12.50	P189

Notes: We provide some general characteristics of the Common Knowledge and Poisson comparative statics sessions. In the first column, we provide the total number of participants in each experiment. The acronyms in the last column consist of the game type (*CK* for Common Knowledge games or *P* for Poisson games), the threshold (13 or 14 or 15 or 16 or 17 or 18) and the fee (9). CK169 and P169 are reproduced from Table 1.

In Figure 2, we plot the proportion of subjects who did not register over different thresholds in the Poisson experiments and the Common Knowledge controls. In both

[19] In CK189, the threshold exceeds the number of subjects commonly known to be in the game. Clearly, it is dominant to abstain from registering. Though the usefulness of this treatment might seem questionable, we decided to conduct it anyway to investigate whether subjects do realize the dominant action. It was comforting to observe 0 registrations in this treatment.

Table 12: DESCRIPTIVE STATISTICS OF THE COMPARATIVE STATICS SESSIONS

Common Knowledge Games

	Registered		Not Registered		Amount
Acronym	Freq.	%	Freq.	%	Awarded?
CK139	10	58.8	7	41.2	No
CK149	9	52.9	8	47.1	No
CK159	9	52.9	8	47.1	No
CK169	16	47.1	18	52.9	No
CK179	3	17.6	14	82.4	No
CK189	0	0.0	17	100.0	No

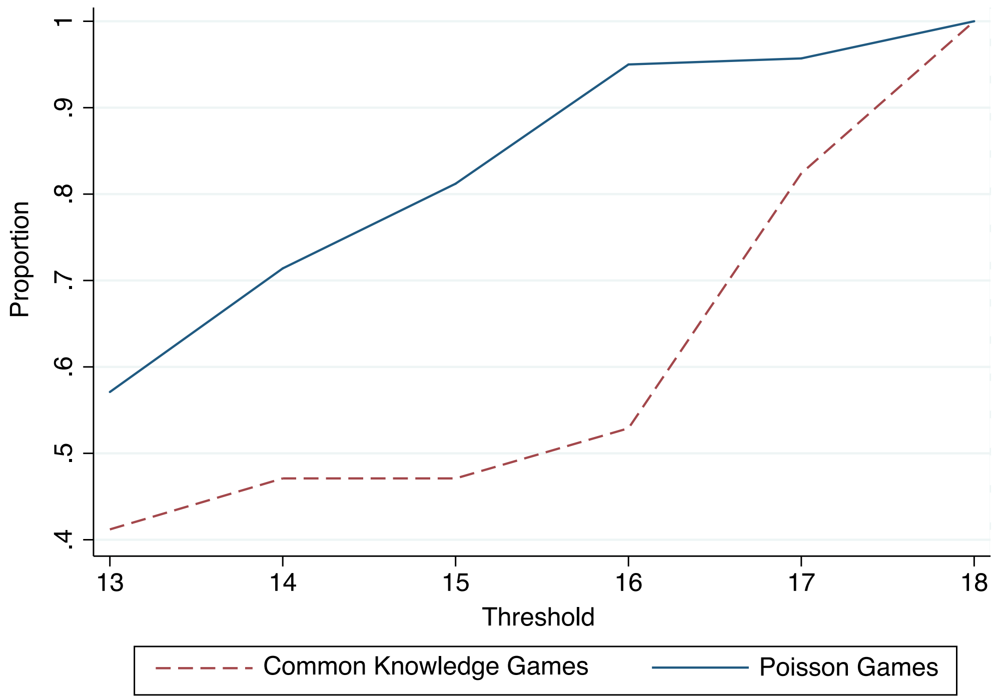
Poisson Games

	Registered		Not Registered		Amount
Acronym	Freq.	%	Freq.	%	Awarded?
P139	9	42.9	12	57.1	No
P149	4	28.6	10	71.4	No
P159	3	18.8	13	81.2	No
P169	2	5.0	38	95.0	No
P179	1	4.3	22	95.7	No
P189	0	0.0	15	100.0	No

Notes: We report the number of subjects who registered, and the number of those who did not register in the Common Knowledge and Poisson comparative statics sessions. In addition, we provide the corresponding percentages. CK169 and P169 are reproduced from Table 2.

cases, the line is non-decreasing for the thresholds investigated. Note that for the threshold levels of $13-15$ and 18, the theoretical prediction in the Poisson and Common Knowledge experiments is the same. Namely, for the threshold levels of $13-15$ either all subjects will register or none of the subjects will register, while for the threshold level of 18, no subject should register. In contrast, for the threshold levels of 16 and 17, in the Poisson experiments, the theoretical prediction is that no subject will register, whereas in the Common Knowledge experiments there is multiplicity of equilibria.

Figure 2: Comparative Statics Over Different Thresholds



Notes: The figure displays the proportion of subjects who did not register over different thresholds in Common Knowledge and Poisson games.

For sufficiently low threshold levels (i.e. 13 and 14), subjects' behavior is statistically similar (the p-values are 0.328 and 0.171, respectively) across the two game types. Presumably, the strategic uncertainty subjects face due to the multiplicity of equilibria, under these threshold levels, leads to similar observed behavior. For threshold levels 15 and 16, subjects' behavior is statistically different across the Poisson experiments and the Common Knowledge controls (the p-values are 0.041 and 0.000, respectively). For threshold level 17, subjects' behavior across both game types is not statistically different (the p-value is 0.166), whereas for threshold level 18 in both game types none of the subjects choose to register. The last two results are not surprising given that for thresholds 17 and 18, the (expected) number of players is weakly lower than the specific threshold levels, which reduces significantly the incentive to register.

Finally, we focus on behavior across thresholds in the Poisson games. Where multiplicity of equilibria is predicted, we still observe a large proportion of subjects not registering, but these proportions are well below the proportion of P169 (i.e. 0.95). We benchmark our statistical analysis on P169 and compare the empirical distribution of that experiment to the ones with the other threshold levels. Comparing P169 and P159, we find that the distributions are marginally statistically similar (the p-value is 0.103). However, when comparing P169 and P149, and P169 and P139, we find that the distributions are statistically different (the p-values are 0.016 and 0.000, respectively). Furthermore, the empirical distribution of P169 is neither statistically different from that of P179 nor from that of P189 (the p-values are 0.907 and 0.378, respectively). These results are in large consistent with the theoretical predictions of the Poisson Coordination games, which postulate different equilibrium outcomes below threshold level 16.

7.2 Limited Depth of Reasoning

Why is there such a large observed difference in the number of subjects choosing to forego registering in the Poisson and Global treatments? One plausible explanation of the large difference may well be that limited depth of reasoning is more likely to guide subjects towards the "safe" action (i.e. foregoing registering) in the Poisson games than in the Global games because even if a subject (a) does not reason at high levels, and (b) believes that it is more likely that the number of other players (in the game) who register is high,[20] there may still be a sizeable probability that there are not enough players in the game. Consequently, the subject may be deterred from registering.[21] We show next that this can indeed be the case by incorporating in our model a very simple version of limited depth of reasoning.[22]

Limited depth of reasoning is a behaviorally-motivated approach that has been shown to explain well *initial* behavior in a variety of environments. In our setup, each player is one of $K+1$ types, $k = 0, 1, ..., K$. Namely, each player can be of

[20]For instance, subjects could apply "team reasoning" where they choose to register to secure the best payoff for the group (see Bacharach (1999)).

[21]We would like to thank an anonymous referee and the Editor for suggesting us to pursue this explanation.

[22]For a discussion of limited-depth-of-reasoning models, and an application of "level-k" thinking in Common Knowledge and Global Coordination games, see Kneeland (2016).

an "L_k" type of bounded depth of reasoning with $k = 0, ..., K$ capturing the depth of reasoning. Players of "level-0" (i.e. L_0) type are not strategic. Each player of "level-1" (i.e. L_1) type believes that all other players are of L_0 type and the number of other players who register is given by a distribution $Q(l|N^-)$ over $l = 0, ..., N^-$ where N^- denotes the actual number of other players in the game. L_2 types believe that all other players are of L_1 type, and so on and so forth.[23]

We further assume that

A3: $\sum_{l=\tilde{l}}^{N^-} Q(l|N^-)$ is non-decreasing in N^-, for all $\tilde{l} = 0, ..., N^-$.

That is, in bigger groups, L_1 types put (weakly) more probability on higher realizations of the number of other players who register.

Turning to the optimal decisions of each type in the Global games, we note that, given assumptions A1-A3, the optimal decisions of L_k types, with $k \geq 1$, are based on signal threshold strategies; that is, L_k types register if the received signal is higher than a threshold signal x^k. Moreover, in Poisson games, L_k types, with $k \geq 1$, register if the commonly known mean n is higher than a threshold mean n^k with $n^K = \cdots = n^2 \geq n^1$ (see the Appendix for the details).

The question now is how does behavior under limited depth of reasoning (i.e. for $1 \leq k \leq K$) change across the incomplete-information game types we focus on. In particular, is it the case that there is $K > k \geq 1$ and $\hat{k}$ with $\hat{k} > k$ such that all $L_{k'}$ types with $k' > k$ do not register in the Poisson game (i.e. $n \leq n^{k'}$) while all $L_{k'}$ types with $k' \leq k$ do register, whereas all $L_{k'}$ types with $k' \leq \hat{k}$ may register in the Global game (i.e. $x > x^{k'}$ for some realized signal x) while, if $\hat{k} < K$, all $L_{k'}$ types with $k' > \hat{k}$ do not? If it turns out that this is the case, then limited depth of reasoning is more likely to lead to fewer registrations in the Poisson games than in the Global games.

Echoing the received literature, we assume that $K \leq 3$.[24] We denote by n^k the mean thresholds under Poisson games, and by x^k the signal thresholds under Global

[23] A general limited-depth-of-reasoning model allows for beliefs to be in general over the whole set of L_k types; see Kneeland (2016) for a discussion. Our assumption here on the beliefs of L_k types is close to the "level-k" model of limited depth of reasoning.

[24] Cornand and Heinemann (2014) and Kneeland (2016) amongst others, argue that reasoning only goes up to three levels in Global games, while Bosworth (2017) shows that reasoning goes up to, at least, two levels in Coordination games. Determining the actual depth of reasoning in Global and Poisson games is an econometric exercise that goes beyond the scope of this paper. We thus defer it for future work.

games.[25] Assuming $Q(l|N^-) = \mathbf{1}_{\{l \geq \lceil \xi N^- \rceil\}} / (N^- + 1 - \lceil \xi N^- \rceil)$ with $\xi = 0.9$,[26] we have that:

- T=9, C=22: $x^1 = 19, x^2 = 25, x^3 = 29$, and $n^1 = 15$ and $n^2 = n^3 = 17$.
- T=10, C=21: $x^1 = 20, x^2 = 26, x^3 = 30$, and $n^1 = 15$ and $n^2 = n^3 = 17$.

Given our experimental parameter choices, regardless of fee T, level-1 types register in the Poisson game, whereas level-2 and level-3 types forego registering (recall that the commonly known mean is $n = 17$). In the Global game, instead, where the set of *a priori* possible realizations of the random signal (given $Y = 25$) are $\{20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30\}$, we have the following. In the case of $T = 9$, level-1 types register, while level-2 and level-3 types may register depending on the signal the subjects receive. In the case of $T = 10$, level-3 types forego registering, while level-1 and level-2 types may register depending on the signal the subjects receive. In summary, subjects may need a much higher level of reasoning to understand the optimality of the safe action under uncertainty associated with the payoff than under Poisson population-size uncertainty. Hence, bounded depth of reasoning is more likely to guide subjects towards foregoing registering in the Poisson games than in the Global games.

8 Concluding Remarks

We study experimentally uncertainty about fundamentals in Coordination games. Specifically, we investigate whether uncertainty about the number of stakeholders or idiosyncratic uncertainty about the profitability of the risky action may influence behavior in the macroeconomy, when these two types of uncertainty lead to a prediction

[25] Thresholds are derived recursively so that every L_k type with $k \geq 1$ best-responds to L_{k-1} type. This implies that if $K = 2$, then the thresholds for $k = 1, 2$ are the same as the ones stated in the main text.

[26] If sufficiently more L_0 types are expected to forego registering, but enough do register, then all level-k types with $k \geq 1$ would forego registering in the Poisson game. For instance, if $\xi = 0.75$, then $n^1 = 17$ and $n^2 = n^3 \geq n^1$. Had we assumed instead that $0 \leq \xi \leq 0.55$, which includes the case of L_0 types described by the uniform distribution (i.e. $Q(\cdot|N^-) = 1/(N^- + 1)$), then, for our experiments, no subject would have registered in either game, should they have been characterized by level-k thinking.

of a unique equilibrium. To do so, we design an online experiment to compare the behavior of subjects in Poisson and Global Coordination games with that in Common Knowledge Coordination games. To the best of our knowledge, this is the first study to investigate experimentally Poisson Coordination games. Poisson Coordination games is a recent approach motivated by the fact that the number of potential speculators is by definition very large in macroeconomic environments. Hence, the standard assumption that every player takes every other player's behavior as given and known when contemplating her best response may be violated. In large societies, for instance, it may be prohibitively expensive to collect the necessary information for who all the stakeholders are. Following the suggestion of Myerson (2000), this approach models the number of actual players as a Poisson random variable.

We find that uncertainty about the number of actual players has a more pronounced impact on subjects' behavior than idiosyncratic uncertainty about economic fundamentals when we focus on parameters for which both Poisson and Global games predict a unique equilibrium.[27] In addition, we find that subjects' behavior in the Poisson Coordination games is closer to the theoretical prediction than subjects' behavior in the Global Coordination games. Finally, a behaviorally-motivated approach based on limited depth of reasoning provides a possible explanation of the experimental results in Global and Poisson games. Consequently, an important avenue for future research could be an econometric analysis of the levels of reasoning under each game type. Such fruitful attempts have been undertaken by Bosworth (2017), Cornand and Heinemann (2014), and Kneeland (2016). However, neither study incorporates Poisson population-size uncertainty.

[27] In particular, subjects' behavior does not differ significantly when comparing Global and Common Knowledge games. A potential explanation could be that subjects have "homemade priors" about the other players' payoff type, which induce similar behavior in Global and Common Knowledge games. Homemade priors refer to subjects' personal beliefs on other players' payoff type(s) that are not induced by the experimenter. The notion of "homemade priors" was introduced by Camerer and Weigelt (1988) to explain deviations from sequential equilibrium predictions in a reputation-formation game. However, testing the hypothesis of "homemade priors" in a systematic way is out of the scope of the current study, and is thus deferred for future research.

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