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THE THEORY OF GLOBAL GAMES ON TEST: EXPERIMENTAL ANALYSIS OF COORDINATION GAMES WITH PUBLIC AND PRIVATE INFORMATION

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The theory of global games has shown that coordination games with multiple equilibria may have a unique equilibrium if certain parameters of the payoff function are private information instead of common knowledge. We report the results of an experiment designed to test the predictions of this theory. Comparing sessions with common and private information, we observe only small differences in behavior. For common information, subjects coordinate on threshold strategies that deviate from the global game solution towards the payoff-dominant equilibrium. For private information, thresholds are closer to the global game solution than for common information. Variations in the payoff function affect behavior as predicted by comparative statics of the global game solution. Predictability of coordination points is about the same for both information conditions.

KEYWORDS: Coordination game, global game, payoff dominance, private information, public information, risk dominance, speculative attack, strategic uncertainty.

1. INTRODUCTION

COORDINATION GAMES WITH STRATEGIC complementarities are a frequently found structure of economic decision problems. Examples are speculative attacks, refinancing debt, choice between market venues, or investment in industries with network effects. In these games, the payoff to some action is positively related to the number of players who take the same action. Strategic complementarities result in multiple equilibria with self-fulfilling beliefs.

The theory of global games, developed by Carlsson and van Damme (1993a, 1993b) and advanced by Morris and Shin (2002), has shown that multiplicity of equilibria is due to common knowledge of the payoff function. If players have only private information, these games have a unique equilibrium. This has led to various applications mainly on financial market issues and to a discussion about the merits of public information.[2] Public information may destabilize an economy by allowing for self-fulfilling beliefs. Predictability of behavior might be lower with public information.

In experimental economics, we distinguish between common information and common knowledge (Smith (1991)). Experiments by, e.g., Stahl and Wilson (1994), Nagel

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[2]See Morris and Shin (1999), Daníelson et al. (2001), Heinemann and Illing (2002), Hellwig (2002), Metz (2002), and Prati and Sbracia (2002).

(1995), and Kübler and Weizsäcker (2004) show that subjects' behavior is more consistent with finite levels of beliefs over beliefs than with theoretical predictions from common knowledge. However, if public information does not create the higher-order beliefs that are responsible for multiple equilibria, then behavior in games with public information may be predictable and the "global-game solution" might be useful as a refinement theory.

We report the results of an experiment designed to test the predictions of the theory of global games. The experiment imitates the speculative-attack model by Morris and Shin (1998). We compare sessions with public and private information. In all sessions, subjects used threshold strategies, i.e. attacked whenever the fundamental state or signal was beyond some critical state or signal. These critical values were surprisingly stable within a session and their variance across sessions was the same for both information conditions. Our evidence suggests that there is no difference in predictability of outcomes that could be related to self-fulfilling features of the game with public information. The main differences in behavior between the two treatments are that with public information, subjects rapidly coordinate on a common threshold, attack more successfully, and achieve higher payoffs than with private information. In the model's interpretation this means that a commitment by the central bank to provide public information increases the prior probability of a speculative attack. But, public information does not reduce the ability to predict at which states of the world an attack occurs.

We also use the experiment to test the predictive power of various refinement concepts. In the game with public information, different refinement criteria select different critical states (thresholds) beyond which attacks occur. Unsurprisingly, all refinements could be rejected numerically. In sessions with public information subjects always coordinate on thresholds somewhere between those associated with payoff-dominant equilibrium and global-game solution. In sessions with private information, strategies deviate from the unique equilibrium towards nonequilibrium profiles with higher average payoffs in treatments where the equilibrium requires coordination of less than half of all subjects, while observed thresholds are distributed around the equilibrium, if this requires coordination of more than half of all subjects. Thresholds respond to parameters of the payoff function in the same way as the global-game solution. We conclude that the global game solution is an important reference point and provides correct predictions for comparative statics with respect to parameters of the payoff function.

Previous experiments on coordination games with strategic complementarities carried out by Van Huyck, Battaglio, and Beil (1990, 1991) have shown that with perfect information subjects coordinate rather quickly. Efficiency depends on group size and experience. While groups of two players often coordinate on the payoff-dominant equilibrium even in unfavorable setups, groups of 14 to 16 players more likely reach inferior equilibria.

Cabrales, Nagel, and Armenter (2003) test the global-game theory in two-person games with random matching inspired by Carlson and van Damme (1993a). Their game has a discrete state space with five possible states and signals, and the global-game solution coincides with maximin strategies. With private information, behavior converges towards the unique equilibrium. With common information, some groups settle on the payoff-dominant equilibrium, others on the global-game solution, and some coordinate on thresholds in between.

Section 2 explains the speculative-attack model used in our experiment. Section 3 lays out the experimental design. In Section 4 we present the main results. Section 5 discusses robustness and Section 6 concludes the paper.

2. SPECULATIVE ATTACKS AS A COORDINATION GAME

Speculative attacks on a currency peg can be modeled as a coordination game with strategic complementarities as in Obstfeld (1996). Traders who expect a devaluation short sell the currency (they attack, as we say) and thereby increase the pressure on the central bank to abandon the peg. If the fundamental state of the economy is really bad, devaluation is inevitable even if nobody attacks, because maintaining the peg is associated with an unsustainable outflow of reserves. In this case, there is a unique equilibrium in which all agents expect devaluation and sell the currency. If fundamentals are sound, the shadow rate is so close to the peg that maximal rewards from an attack are too small to cover transaction costs. Here, it is irrational to attack. In intermediate situations, beliefs are self-fulfilling: if a sufficient number of traders expects a devaluation, their short sales create a market pressure that forces the central bank to give up the peg that it would have maintained otherwise.

In our experiment we employ a reduced game form based on Morris and Shin (1998) with a finite number of traders n, who decide simultaneously whether to attack or not. An attack is associated with opportunity costs T. If the currency is devalued each attacking agent earns an amount Y, which is the difference between currency peg and shadow exchange rate. The lower Y, the higher is the shadow rate and the better is the state of the economy. An attack is successful if and only if a sufficient number of traders decides to attack. The hurdle to success is higher for better states of the economy and modelled as a nonincreasing function in Y. Let $a(Y)$ be the number of players who are needed to enforce a devaluation and assume $a' \leq 0$ and $1 < a(T) \leq n$. Figure 1 shows

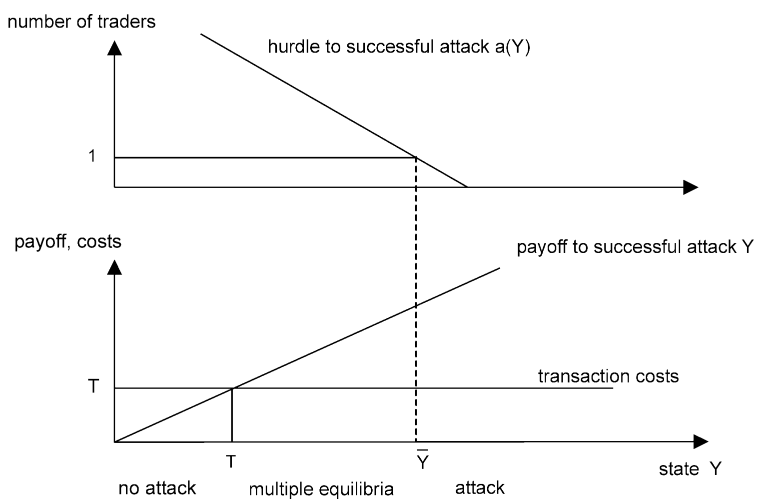

FIGURE 1.—The speculative attack game.

the hurdle to successful attacks and the payoff function for this game. If at least $a(Y)$ traders attack, attacking players receive a payoff $Y - T$. Nonattacking players receive 0.

If state Y is common information (CI), the game has multiple equilibria for some Y. We can distinguish three regions for Y.

(i) If $Y < T$, payoffs from attacking are always smaller than opportunity costs. It is a dominant strategy not to attack.

(ii) If $Y > \overline{Y} = a^{-1}(1)$, a single trader can enforce a devaluation. It is a dominant strategy to attack.

(iii) If $T < Y < \overline{Y}$, there are two Nash equilibria in pure strategies: either all players attack and receive a reward above opportunity costs, or no player attacks and a single attacking trader would lose T.

A refinement theory selects a unique threshold state up to which players do not attack and above which all players attack.

The payoff-dominant equilibrium, recommended by Harsanyi and Selten (1988), prescribes to attack if and only if $Y > T$, and hence the threshold is $Y = T$.

The maximin strategy prescribes to attack if and only if success does not depend on other subjects' decisions. Its threshold is $Y = \overline{Y}$.

Applying the global game approach, Morris and Shin (1998) assume that the fundamental state Y has a uniform distribution in $[T - \delta, T + \delta]$. Players do not know the state, but receive private signals x^i randomly drawn with independent and uniform conditional distributions on $[Y - \varepsilon, Y + \varepsilon]$, where $\varepsilon \leq \delta$. This private information game has a unique equilibrium with a threshold signal X^*, such that players attack, if and only if they receive a signal above this threshold. A risk neutral player who receives the marginal signal X^* is indifferent between attacking and not attacking provided that all other players attack if and only if they receive signals above X^*. At state Y the probability that a players' attack is successful is given by the probability that at least $a(Y) - 1$ out of the other $n - 1$ players get signals above X^* and attack. This can be described by the binomial distribution. The probability that a single player gets a signal above X^* at state Y is $(Y - X^* + \varepsilon)/(2\varepsilon)$. Denoting the round-up of $a(Y)$ by $\hat{a}(Y)$, the expected payoff of an attacking agent with the marginal signal is

$$EU(X^*) = \frac{1}{2\varepsilon} \int_{X^*-\varepsilon}^{X^*+\varepsilon} Y\left[1 - \text{Bin}\left(\hat{a}(Y) - 2, n - 1, \frac{Y - X^* + \varepsilon}{2\varepsilon}\right)\right] dY,$$

where Bin is the cumulative binomial distribution. The equilibrium threshold signal X^* is defined by $EU(X^*) = T$. For states in an ε-surrounding of X^* the number of attacking agents and the success of an attack depend on the random draws of individual signals. Hence, there is no threshold state that divides successful from failed attacks for $\varepsilon > 0$.

Heinemann (2000) shows that for ε converging to zero, the threshold signal X^* approaches a state Y^*, given by the unique solution to $Y^*[n - \hat{a}(Y^*) + 1] = nT$. This limit point for diminishing variance of private signals is independent from other assumptions on the probability distributions (Frankel, Morris, and Pauzner (2003)). Morris and Shin (2002) point out that Y^* is the optimal threshold of a player who believes that the proportion of attacking players has a uniform distribution in $[0, 1]$. It can be used as a refinement theory for the common-information game. Henceforth, we refer to threshold Y^* as the "global-game solution" for the game with common information.

Another well-known refinement theory is the risk-dominant equilibrium, defined by Harsanyi and Selten (1988). The risk-dominant strategy is the optimal strategy of a player who believes that other players believe that the probability of success has a uniform distribution in [0, 1]. Its threshold is given by the solution to $Y[1 - \text{Bin}(\hat{a}(Y) - 2, n - 1, 1 - T/Y)] = T$. For $n = 2$, the risk-dominant equilibrium coincides with the global-game solution.

In our experiment, we avoided any connotation that might be associated with "speculation" or "attacking." We just asked subjects to choose between two actions A and B. In order to avoid negative payoffs, Action A was introduced as a secure alternative, yielding a positive and constant payoff that may be interpreted as opportunity costs of a speculative attack T. Action B was the risky action, yielding a payoff of Y if the number of subjects choosing B exceeds a hurdle function $a(Y)$ and zero otherwise.

3. EXPERIMENTAL DESIGN

Sessions were run at a PC pool in the Economics Department at the University of Frankfurt and in the LEEX at Universitat Pompeu Fabra, Barcelona, from November 2000 until June 2001.[3] In both places, most of the participants were business and economics undergraduates. The procedure during the sessions was kept the same throughout all sessions at both places, besides the languages (German and Spanish, respectively). All sessions were computerized, using a program done with z-tree (Fischbacher (1999)). Instructions[4] were read aloud and questions were answered in private. Throughout the sessions students were not allowed to communicate and could not see others' screens.

We ran 14 sessions with common information (CI) and 15 sessions with private information (PI) (see Table I). In each session there were 15 participants. For two sessions with CI we re-invited subjects with experience in previous sessions. In total, 405 students participated. 27 sessions consisted of two stages of 8 independent rounds each. In each round all subjects had to decide between two alternatives A and B for 10 independent situations.

For each situation, a state Y, the same for all subjects, was randomly selected from a uniform distribution in the interval [10, 90]. In sessions with CI, players were informed about Y. In sessions with PI, this information was withheld. Instead, each subject received a private signal, independently and randomly drawn from a uniform distribution in the interval $[Y - 10, Y + 10]$. These numbers were displayed with three decimal digits. We did not order the states or signals in order not to induce so-called threshold strategies.

The payoff for alternative A was T experimental currency units (ECU) with certainty. The two stages of each session differed by the parameter T. In half of all sessions we started with $T = 20$ and switched to $T = 50$ in the second stage and vice versa for the other half. The payoff for B was Y ECU, if at least $a(Y) = 15(80 - Y)/Z$ subjects chose B, zero otherwise. The formula was written in the instructions, but also explained with an example and a table. In four sessions we applied $Z = 100$, in the others $Z = 60$.

[3]Four additional sessions with high stakes or more repetitions were run in March 2003.

[4]Instructions are available from the authors upon request and can also be found in the working paper version, Heinemann, Nagel, and Ockenfels (2002).

TABLE I
SESSION OVERVIEW

				Number of Sessions with	
Z	Secure Payoff T	Location	Session Type	Common Information	Private Information
100	1st stage 20/2nd stage 50	Frankfurt	Standard	1	1
100	50/20	Frankfurt	Standard	1	1
60	20/50	Frankfurt	Standard	1	2
60	20/50	Barcelona	Standard	3	3
60	50/20	Frankfurt	Standard	2	2
60	50/20	Barcelona	Standard	3	3
60	20/50	Frankfurt	Experienced subjects	1	
60	50/20	Frankfurt	Experienced subjects	1	
60	50	Barcelona	40 periods		2
60	20/50	Barcelona	High-stake		1
60	50/20	Barcelona	High-stake	1	
Total number of sessions				14	15

All parameters of the game and the rules were common information except for drawn states Y and private signals in the PI sessions.

Once all players had completed their decisions in one round, they saw—for each situation—their own private signal (in PI-sessions), the value of Y, their choice, how many people had chosen B, whether action B was successful or not, their individual payoffs, and the cumulative payoff over all 10 situations. After all players had left the information screen a new period started and information of previous periods could not be revisited. Subjects were allowed to take notes and many of them did.

At the end of each session participants had to write in a questionnaire (via computer) their personal data, respond to four questions about their behavior and were free to give additional comments regarding the experiment. Once the questionnaire was completed, each person was paid in private, converting their total points into DM, Pesetas, or Euro, respectively. In sessions with $Z = 100$: 1000 ECU = 4 DM (€2.05). In sessions with $Z = 60$, 1000 ECU were converted to 5 DM (€2.56) in Frankfurt and to 300–400 Pesetas (€1.80–2.40) in Barcelona. In standard sessions, average payment per subject varied across sessions from €14 to €22. Session length was between 75 and 120 minutes.

Standard sessions (see Table I) were used for various statistical analyses, some of which are reported in the next section.[5] The additional 6 sessions were introduced for robustness checks, summarized in Section 5. For two sessions with CI we re-invited subjects with experience in previous sessions. Two sessions with PI had only one treatment ($T = 50$) that was kept for 40 periods. Here, 1000 ECU were converted to €1. The duration of these sessions was about 120 minutes and subjects received €23 on av-

[5]Additional analyses can be found in the working paper version, Heinemann, Nagel, and Ockenfels (2002).

erage. In two "high-stake sessions," subjects were paid €1 for 1 ECU for two randomly selected decision situations, one from each treatment. They earned €101 on average.

4. RESULTS

In each period, subjects chose A or B for 10 randomly chosen unordered situations. With this design we can check the use of threshold strategies without imposing such a structure. Behavior is "consistent with a threshold strategy," if A is chosen for low states (CI-treatments) or signals (PI-treatments) and B is chosen for high states or signals with at most one switching point. A threshold strategy is dominated in CI-treatment if B is chosen for $Y < T$ or A is chosen for $Y > \overline{Y}$. In PI-treatments B is dominated by A when signal $X^i < T - \varepsilon$ and A by B when $X^i > \overline{Y} + \varepsilon$.

RESULT 1 (Undominated Thresholds): An average of 92% of all strategies is consistent with undominated thresholds.

There is no significant difference between common and private information sessions, or between treatments with different parameters. In Barcelona the average number of subjects using undominated thresholds is 4% smaller than in Frankfurt. In a simple regression the location dummy is significant at the 5% level. We cannot explain this difference.

Figure 2 shows that the proportion of undominated threshold strategies increased over time, although with the change of treatment in period 9, we observed this number to drop, especially in Barcelona.

It is intuitive to play threshold strategies since the hurdle for success of B decreases in Y, while the payoff to a successful B increases. Threshold strategies reduce the perceived complexity of the decision problem. However, deductive reasoning needs very strong assumptions: With private information, theory predicts threshold strategies but requires common knowledge of rationality. With common information nonthreshold strategies may even occur in Nash equilibria. The strength of threshold strategies lies in their robustness: if a subject expects others to play threshold strategies or to randomize, best response is a threshold strategy. Other strategies are not robust against even slightest deviations from common knowledge.

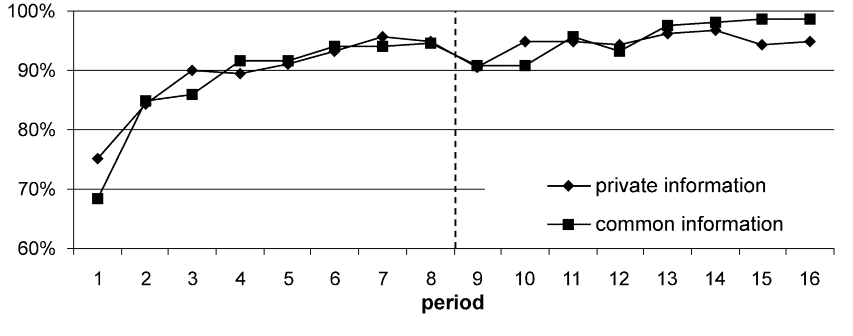

FIGURE 2.—Percentage of inexperienced subjects, whose behavior is consistent with undominated threshold strategies.

Because of the common use of thresholds we can estimate the probability with which a subject chooses B by fitting a logistic distribution function to observed choices. Results may be interpreted in two ways: (i) as estimated probabilities for subjects choosing B conditional on state Y or signal X, respectively, (ii) as estimated distribution of individual thresholds. The cumulative logistic distribution is given by

$$\text{prob}(\text{B}) = \frac{1}{1 + \exp(a - bX)}.$$

Its mean, a/b, is interpreted as mean threshold of the group. Its standard deviation $\pi/(b\sqrt{3})$ is a measure of coordination and tells us how much individual thresholds vary within a group.

Parameters a and b can be estimated from data of single periods or by combining data from several periods. Estimates based on single periods do not show much variation after the first three periods of each treatment. This is in line with a general impression that individual behavior does not change much after the first periods. Therefore, we can improve the quality of estimates by combining data of the last four rounds of each treatment.

Table VI in the Appendix gives results of these estimates for all sessions. Table II compares equilibrium thresholds with a summary statistic of estimated means and standard deviations from all standard sessions. In addition, we give the standard deviation

TABLE II

ESTIMATED MEAN THRESHOLDS AND THEORETICAL EQUILIBRIA

Treatment	$T=20, Z=100$	$T=20, Z=60$	$T=50, Z=100$	$T=50, Z=60$
Sessions with PI				
Average estimated mean threshold	29.73	41.83	55.33	57.04
Average estimated standard deviation of thresholds within a session	8.31	9.49	8.45	9.31
Standard deviation of estimated mean thresholds across sessions		4.15		3.43
Number of sessions	2	10	2	10
Equilibrium threshold X^*	32.36	41.84	60.98	66.03
Sessions with CI				
Average estimated mean threshold	26.71	37.62	52.84	53.20
Average estimated standard deviation of thresholds within a session	4.13	6.23	5.29	5.92
Standard deviation of estimated mean thresholds across sessions		3.50		3.67
Number of sessions	2	9	2	9
Payoff-dominant equilibrium T	20	20	50	50
Global-game solution Y^*	33.33	44	60	64
Risk-dominant equilibrium	34.55	44	62.45	67.40
Maximin-strategy threshold $\overline{Y}$	73.33	76	73.33	76
Optimal threshold given all other players choose B with probability 2/3	23.52	40.00	50.04	52.00

of estimated mean thresholds across sessions for those treatments that have been used in more than two sessions.

In the remainder of this section we explain results obtained from statistical analyses of estimated mean thresholds. Some of these results are already visible in Table II.

RESULT 2 (PI-Thresholds): In sessions with PI, estimated mean thresholds are close to or below the unique equilibrium.

Using a two-sided F-test, we cannot reject that estimated thresholds are equal to the unique equilibrium in treatments with $T = 20$. For $T = 50$ estimated mean thresholds are *all* clearly below the equilibrium. Here, a two-sided F-test rejects the equilibrium prediction at a p-level of 1%.

RESULT 3 (CI-Thresholds): In sessions with CI, estimated mean thresholds are between the thresholds of the payoff-dominant equilibrium and the global-game solution. They are closer to the optimal threshold of a player who believes that other players choose B with probability 2/3 for any state.

Global-game solution, risk-dominant equilibrium, and maximin strategies can be rejected at a p-level of 1% using a two-sided F-test for data with $T = 20$ and $T = 50$. For $T = 20$, payoff dominance can also be rejected at a p-level of 1%. For $T = 50$ estimated thresholds come rather close to the payoff-dominant equilibrium (53 for both Z-values), although the difference is still significant at 4%. A more general approach is a theory that assumes beliefs about individual choices instead of aggregates. If a player believes that every other player chooses B with some probability p, the best response is a threshold Y, solving $Y[1 - \text{Bin}(\hat{a}(Y) - 2, n - 1, p)] = T$. For $p \in (.6, .7)$ this theory cannot be rejected.

In both information conditions deviations from the global-game solution or the PI equilibrium, respectively, are larger in treatments with $T = 50$ than in treatments with $T = 20$. The reason might be that at higher states, success of the risky action requires coordination of a smaller number of players and is thereby associated with less strategic uncertainty.

RESULT 4 (Comparative Statics): In both information conditions, estimated mean thresholds follow the comparative statics of global-game solution and risk-dominant equilibrium for variations of T or Z.

For a systematic analysis of the influence of information and other controlled variables on mean thresholds in standard sessions, we use linear regressions. Table III explains the variables. To control for a nonlinearity in the payoff function, our regressions include an interaction variable TZ that equals one if and only if $T = 50$ and $Z = 60$. Variable TO is included to capture the different size of the order effect in the two stages. Regression results are summarized in Table IV.

Regressions 1, 3 and 4: $a/b = \alpha_0 + \alpha_1 T + \alpha_2 Z + \alpha_3 TZ + u$.

Regression 2: $a/b = \alpha_0 + \alpha_1 T + \alpha_2 Z + \alpha_3 TZ + \alpha_4 Loc + \alpha_5 Info + \alpha_6 Ord + \alpha_7 TO + u$.

Regression 5: $\pi/(b\sqrt{3}) = \alpha_0 + \alpha_1 T + \alpha_2 Z + \alpha_3 TZ + \alpha_4 Loc + \alpha_5 Info + \alpha_6 Ord + \alpha_7 TO + u$.

TABLE III

VARIABLES USED IN REGRESSIONS

Name	Nature	Definition	
T	Dummy	0: payoff for secure action $T = 20$	1: $T = 50$
Z	Dummy	0: session with $Z = 100$	1: session with $Z = 60$
TZ	Dummy	0: if $T = 20$ or $Z = 100$	1: if $T = 50$ and $Z = 60$
Loc(ation)	Dummy	0: session in Barcelona	1: session in Frankfurt
Info(rmation)	Dummy	0: session with CI	1: session with PI
Ord(er)	Dummy	0: session starting with $T = 50$	1: session starting with $T = 20$
TO	Dummy	0: if $Ord = 0$ or $T = 20$	1: if $Ord = 1$ and $T = 50$
a/b	Real	Estimated mean threshold a/b as given in Table VI	
$\pi/(b\sqrt{3})$	Real	Estimated standard deviation of thresholds within a session	

Our regression results show that estimated thresholds increase with T and Z and the effect of a simultaneous increase in T and Z is smaller than the sum of the effects of either parameter change in isolation (TZ has a negative impact). These effects are precisely as predicted by the theory of global games and by the risk-dominant equilibrium, while the payoff-dominant equilibrium does not respond to changes in Z and the maximin strategy is independent from T. Separate regressions for treatments with common and private information yield the same results. Regression 1 shows that T and Z explain 83.8% of all data variation. Regression 2 shows that information, location, and the order of treatments increase this to 91.4%. We conclude that global-game solution and risk dominance are suitable refinements for the purpose of comparative statics with respect to parameters of the payoff function.

The higher the threshold to success, the smaller is ex-ante probability for states at which subjects succeed to play B. In the speculative attack game, this is interpreted as a lower prior probability for attacks that enforce devaluation. Our results confirm the

TABLE IV

REGRESSIONS 1 TO 5

No.	Data Source (Number of Observations)	Estimated Coefficients α_i (t-Values): Intercept	T	Z	TZ	*Loc*	*Info*	*Ord*	TO	R^2 Adj. R^2
1	All treatments	28.22	25.86	11.61	−10.48					.84
	(46)	(13.42)	(8.70)	(5.02)	(−3.20)					.83
2	All treatments	22.62	27.61	12.40	−10.57	1.18	3.58	5.29	−3.50	.91
	(46)	(10.77)	(11.22)	(6.54)	(−4.23)	(1.09)	(3.76)	(3.94)	(−1.90)	.90
3	Treatments	26.72	26.12	10.90	−10.54					.87
	with CI (22)	(9.40)	(6.50)	(3.47)	(−2.37)					.84
4	Treatments	29.73	25.60	12.09	−10.39					.87
	with PI (24)	(11.17)	(6.80)	(4.15)	(−2.52)					.86
5	All treatments	2.97	2.53	2.95	−.96	1.49	2.29	2.90	−4.00	.36
	(46)	(1.67)	(1.21)	(1.83)	(−.45)	(1.62)	(2.84)	(2.54)	(−2.48)	.24

theoretical predictions by Morris and Shin (1998) and Heinemann (2000) that transaction costs (T) and capital controls (hurdle function) are effective means to reduce the probability of currency crises.

RESULT 5 (Information Effect): In sessions with PI, estimated mean thresholds are higher than in sessions with CI.

Regression 3 above shows that with CI, thresholds tend to be 3.58 units lower than with private information. This difference is significant at 1%. It implies that public information reduces the thresholds to attack and increases the prior probability of devaluation in the speculative attack game.

RESULT 6 (Order Effect): In sessions starting with $T = 50$, estimated mean thresholds are lower than in sessions starting with $T = 20$.

Surprisingly, regression 3 shows that thresholds tend to be higher in sessions starting with a low payoff for the secure action ($T = 20$) than in sessions starting with a high payoff ($T = 50$). Originally we expected the opposite result. With slow convergence to a new threshold, the threshold for $T = 20$ should be higher after a treatment starting with $T = 50$ than in a session that starts with $T = 20$. Similarly, after a treatment with $T = 20$ the threshold for $T = 50$ should be lower than in a session that starts with $T = 50$. In the questionnaire, many subjects reported that they played B for all signals or states that were some increment δ^i above T, where δ^i was sometimes reported as being 10 or 20 and gradually adjusted with experience. The order effect is consistent with a numerical inertia in these increments δ^i. This may be relevant to predict adjustments over time to changing environments of coordination games.

RESULT 7 (Coordination): In sessions with PI, the standard deviation of individual thresholds within a sessions is larger than in sessions with CI.

Regression 5 shows that the estimated standard deviation of individual thresholds within a session is larger for private than for common information. In sessions with CI, most subjects coordinate on a common threshold within a few periods. Once coordination by a large number of subjects is achieved, the threshold does not change anymore. In sessions with PI, individual thresholds gradually converge to each other. The process of convergence has not settled after eight periods which will be further discussed in the section about robustness.

RESULT 8 (Predictability): The dispersion of mean thresholds across different sessions is about the same for both information conditions.

The information structure influences predictability of successful speculative attacks in two ways: (i) CI might reduce predictability of strategies, because they might be driven by self-fulfilling beliefs; (ii) conditional on the knowledge about strategies, PI reduces the predictability of the aggregate outcome due to the random nature of signals. The main objection against public information comes from fears that strategies could be driven by self-fulfilling beliefs.

Comparing the standard deviation of mean thresholds across sessions in Table II above, it seems that the information condition has no big impact on the dispersion of observed thresholds among otherwise equal treatments. This impression is supported by separate regressions of thresholds for both information conditions. In both data subsets, parameters of the payoff function explain 87% of the data variation (see regressions 3 and 4). The average value of residuals is 3.63 in treatments with CI and 3.44 in treatments with PI. Thus, there is no extra volatility that could be attributed to self-fulfilling features of the game with CI.

5. ROBUSTNESS

We ran six nonstandard sessions to check the robustness of our results. These sessions were designed to address the impact of a potential lack of comprehension (sessions with experienced players), lack of motivation (sessions with high payoffs), or lack of time to see thresholds converge to the unique equilibrium in the PI-setting with $T = 50$ (sessions with 40 rounds).

Sessions with experienced players show a somewhat higher proportion of threshold strategies than standard sessions (83% instead of 72% in the first period and 97% instead of 92% in total). These differences are not significant, though. Interpreting the proportion of threshold strategies as a measure of comprehension and motivation, we conclude that there is no indication for a substantial lack of comprehension or motivation in standard sessions.

In the two high-stake sessions, we randomly selected two decision situations (one from each stage) to determine the payoff. The average payoff for a selected situation was €50.50, while in standard sessions the average payoff per decision was about 12 cent. High payoffs raise the incentives to decide carefully and to abstain from testing out the experimental set-up. Holt and Laury (2002) show in a lottery experiment that high payoffs do also increase risk aversion. Payoffs in our high-stake treatments are comparable to their 20×-treatment, for which they found that most subjects have a relative risk aversion of 0.4 to 0.6.[6] Higher payoffs increase observed thresholds in the experiment and risk aversion raises the threshold of the global-game solution (see Table V).

Estimated mean thresholds in high-stake sessions are higher than in any of the otherwise equal treatments with low payoffs (see Table VI, Appendix). This is another support for the comparative-statics predictions of the theory of global games with respect to changes in the payoff function. In both sessions, thresholds for $T = 50$ are below the global-game solution for risk averse players and even lower than the theoretical thresholds based on risk neutrality, which are 66.03 (PI) and 64 (CI). For $T = 20$, the threshold in the CI session is below the global-game solution for reasonable levels of risk aversion. In the PI session, the threshold for $T = 20$ is in the range predicted by the equilibrium for a relative risk aversion around .5. These observations are in line with results from standard sessions. Thresholds also show the same relative ordering between different treatments that we observe in standard sessions. The gap between thresholds from the two information conditions is larger than between standard sessions with PI and CI. This is in line with the order effect (Result 6), because we started the PI-session

[6]These low estimates are due to neglecting initial wealth.

TABLE V

ESTIMATED MEAN THRESHOLDS AND THEORETICAL PREDICTIONS FOR HIGH PAYOFFS

			Estimated Mean Threshold		PI Equilibrium/Global-Game Solution for Relative Risk Aversion of .5[a]	
Session	Information	Order	For $T = 20$	For $T = 50$	For $T = 20$	For $T = 50$
H1	PI	20/50	56.79	65.07	54.64	73.16
H2	CI	50/20	46.56	56.58	56	68

[a] Equilibrium thresholds have been calculated using the constant relative risk aversion utility function $U(x) = x^{1-r}$, where r is relative risk aversion and x the payoff from the experiment.

(H1) with a safe payoff $T = 20$, where we could expect the highest threshold, while the CI-session (H2) was started with $T = 50$.

We ran two sessions with 40 periods, PI and $T = 50$, because in all standard sessions with PI thresholds for $T = 50$ stayed below the equilibrium within the eight periods. This is surprising, given that the equilibrium is the unique strategy surviving an iterated elimination of dominated strategies. With thorough calculations and enough repetitions, subjects should become aware that they can improve individual payoffs by a unilateral increase of their thresholds. In the long sessions, 20 out of 30 participants reported that they did not change their thresholds after period 20. For comparability with standard sessions, we estimate mean thresholds by combining data from four subsequent rounds in each session. Figure 3 shows that there is no tendency towards the equilibrium.[7] This behavior violates individual rationality, but it leads to higher average payoffs than equilibrium strategies, due to strategic complementarities.

Estimated standard deviations of final thresholds within each of the two sessions are 4.8 and 5.1 and, thereby, smaller than in any of the standard sessions with PI (see Table VI, Appendix). They are comparable to standard deviations of thresholds in sessions with CI, where subjects were extremely well coordinated after eight rounds. This shows that subjects are able to achieve a high degree of coordination in their thresh-

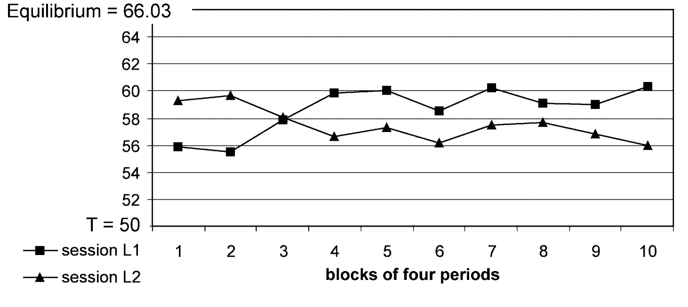

FIGURE 3.—Estimated mean thresholds in the two sessions with 40 periods.

[7] The small differences in estimated average thresholds between the last blocks can be explained by the random selection of states and signals.

old signals even with PI. This process had not settled after eight rounds. But, the final threshold after 40 periods is closer to the average threshold after eight periods than to the equilibrium.

6. CONCLUSIONS

The theory of global games provides an appealing solution to coordination games with strategic complementarities. Our experiment confirms that in both information conditions, most subjects use threshold strategies, and estimated mean thresholds follow the comparative statics of the global-game solution with respect to parameters of the payoff function. In the theoretical literature, the discussion about global games is focusing on the effects of public versus private information. The main problem is that public information restores multiplicity, if it is sufficiently precise compared with private information. From our experiment we conclude that in real decision situations, public information does not generate self-fulfilling beliefs. Predictability of thresholds is about the same for both information conditions.

In our view, limited levels of reasoning about other players' strategies and strategic uncertainty are the major forces that drive subjects to play threshold strategies, lead to the low variation of observed thresholds, and also explain some of the comparative statics. With limited levels of reasoning, common information does not become common knowledge. There remains uncertainty about higher order beliefs. In sessions with PI, strategic uncertainty may be lower, but it adds to uncertainty from random signals. This may explain, why observed thresholds are higher for PI than for CI. At higher states, success of the risky action requires coordination of a smaller number of players and is thereby associated with less strategic uncertainty. This may explain why deviations from the global-game solution were larger in treatments with $T = 50$ than in treatments with $T = 20$.

The current discussion on the optimal modes of information disclosure by central banks concentrates on the multiplicity of equilibria associated with public information. Our experiment suggests that this may be a subordinate effect. Thresholds to successful speculative attacks (in the game's interpretation) were fairly predictable for both information conditions. The major effect seems to be that public information reduces the threshold to attack, and a commitment to provide public information raises the prior probability of currency crises.

With public information the central bank has more control over traders' beliefs than when they get private information from other sources. Uncontrolled information reduces the ability of the central bank to predict an attack. This loss in predictability, which is modelled by the random nature of private signals in our experiment, outweighs the loss of predictability that may be induced by self-fulfilling beliefs under public information. The results of our experiment indicate that both effects are small when the number of traders is sufficiently large. For games with fewer players, both effects gain importance and it is an open question which one is bigger then.

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APPENDIX: LOGISTIC ESTIMATION OF INDIVIDUAL THRESHOLDS

Table VI displays the results of logistic regressions to estimate mean and standard deviation of individual thresholds in each session and treatment based on observations from the last four periods.

TABLE VI

RESULTS OF LOGISTIC REGRESSIONS

Session	Type	Location	Z	Infor-mation	Order	T	Parameter Estimation a	Parameter Estimation b	Estimated Mean a/b	Estimated Standard Deviation
P1	Standard	Frankfurt	100	PI	20/50	20	5.07	.155	32.76	11.72
						50	11.13	.196	56.77	9.25
P2	Standard	Frankfurt	100	PI	50/20	50	12.78	.237	53.90	7.65
						20	9.88	.370	26.71	4.90
C1	Standard	Frankfurt	100	CI	20/50	20	10.32	.311	33.21	5.84
						50	67.43	1.265	53.31	1.43
C2	Standard	Frankfurt	100	CI	50/20	50	10.37	.198	52.37	9.16
						20	15.16	.750	20.22	2.42
P3	Standard	Frankfurt	60	PI	20/50	20	5.67	.123	46.04	14.73
						50	7.15	.119	60.32	15.30
P4	Standard	Frankfurt	60	PI	50/20	50	7.85	.134	58.59	13.53
						20	7.29	.157	46.57	11.59
P5	Standard	Frankfurt	60	PI	50/20	50	12.79	.211	60.71	8.61
						20	11.92	.289	41.22	6.27
P6	Standard	Frankfurt	60	PI	20/50	20	7.40	.166	44.57	10.93
						50	18.37	.305	60.29	5.95
C3	Standard	Frankfurt	60	CI	20/50	20	9.13	.239	38.20	7.59
						50	36.28	.635	57.09	2.85
C4	Standard	Frankfurt	60	CI	50/20	50	8.08	.177	45.67	10.25
						20	10.32	.314	32.81	5.77
C5	Standard	Frankfurt	60	CI	50/20	50	330.25	6.402	51.58	.28
						20	14.24	.443	32.16	4.10
P7	Standard	Barcelona	60	PI	20/50	20	7.94	.185	42.84	9.79
						50	7.82	.144	54.16	12.57
P8	Standard	Barcelona	60	PI	50/20	50	14.09	.264	53.35	6.87
						20	10.52	.291	36.18	6.24
P9	Standard	Barcelona	60	PI	20/50	20	7.51	.167	44.86	10.83
						50	16.68	.326	51.24	5.57
P10	Standard	Barcelona	60	PI	50/20	50	10.32	.188	55.00	9.66
						20	9.88	.259	38.14	7.00
P11	Standard	Barcelona	60	PI	20/50	20	8.08	.188	43.09	9.67
						50	14.82	.247	60.01	7.35
P12	Standard	Barcelona	60	PI	50/20	50	13.45	.237	56.73	7.65
						20	8.02	.231	34.78	7.86

TABLE VI (*continued*)

Session	Type	Location	Z	Information	Order	T	Parameter Estimation a	Parameter Estimation b	Estimated Mean a/b	Estimated Standard Deviation
C 6	Standard	Barcelona	60	CI	20/50	20	6.33	.162	39.10	11.20
						50	11.35	.223	50.87	8.13
C 7	Standard	Barcelona	60	CI	50/20	50	23.33	.430	54.25	4.22
						20	17.61	.490	35.96	3.70
C8	Standard	Barcelona	60	CI	20/50	20	25.71	.639	40.26	2.84
						50	73.82	1.356	54.44	1.34
C9	Standard	Barcelona	60	CI	50/20	50	8.75	.158	55.49	11.50
						20	14.36	.340	42.22	5.33
C10	Standard	Barcelona	60	CI	20/50	20	6.31	.154	40.94	11.77
						50	10.11	.176	57.50	10.31
C11	Standard	Barcelona	60	CI	50/20	50	21.36	.411	51.91	4.41
						20	17.59	.477	36.92	3.81
E1	Experienced	Frankfurt	60	CI	20/50	20	18.19	.557	32.66	3.26
						50	28.83	.505	57.06	3.59
E2	Experienced	Frankfurt	60	CI	50/20	50	85.88	1.707	50.32	1.06
						20	16.09	.518	31.06	3.50
L1	Long	Barcelona	60	PI	—	50	22.78	.378	60.36	4.81
L2	Long	Barcelona	60	PI	—	50	19.96	.357	55.96	5.09
H1	High stake	Barcelona	60	PI	20/50	20	8.38	.148	56.79	12.29
						50	10.12	.156	65.07	11.66
H2	High stake	Barcelona	60	CI	50/20	50	37.79	.668	56.58	2.72
						20	46.56	6.051	46.56	6.05

REFERENCES

CABRALES, A., R. NAGEL, AND R. ARMENTER (2003): "Equilibrium Selection Through Incomplete Information in Coordination Games: An Experimental Study," Discussion Paper No. 601, Universitat Pompeu Fabra, Barcelona.

CARLSSON, H., AND E. VAN DAMME (1993a): "Global Games and Equilibrium Selection," *Econometrica*, 61, 989–1018.

——— (1993b): "Equilibrium Selection in Stag Hunt Games," in *Frontiers of Game Theory*, ed. by K. Binmore, A. Kirman, and P. Tani. Cambridge, MA: MIT Press, 237–253.

DANÍELSON, J., P. EMBRECHTS, C. GOODHART, F. MUENNICH, AND H. S. SHIN (2001): "An Academic Response to Basel II," Financial Markets Group Special Paper No. 130, London School of Economics.

FISCHBACHER, U. (1999): "*z*-Tree 1.1.0.: Experimenter's Manual," University of Zurich, Institute for Empirical Research in Economics, http://www.iew.unizh.ch/ztree/index.php.

FRANKEL, D., S. MORRIS, AND A. PAUZNER (2003): "Equilibrium Selection in Global Games with Strategic Complementarities," *Journal of Economic Theory*, 108, 1–44.

HARSANYI, J. C., AND R. SELTEN (1988): *A General Theory of Equilibrium Selection in Games.* Cambridge, MA: MIT Press.

HEINEMANN, F. (2000): "Unique Equilibrium in a Model of Self-Fulfilling Currency Attacks: Comment," *American Economic Review*, 90, 316–318.

HEINEMANN, F., AND G. ILLING (2002): "Speculative Attacks: Unique Sunspot Equilibrium and Transparency," *Journal of International Economics*, 58, 429–450.

HEINEMANN, F., R. NAGEL, AND P. OCKENFELS (2002): "Speculative Attacks and Financial Architecture: Experimental Analysis of Coordination Games with Public and Private Information," London School of Economics, Financial Markets Group Working Paper dp416, http://www.sfm.vwl.uni-muenchen.de/heinemann/publics/hno-1.htm.

HELLWIG, C. (2002): "Public Information, Private Information, and the Multiplicity of Equilibria in Coordination Games," *Journal of Economic Theory*, 107, 191–222.

HOLT, C. A., AND S. K. LAURY (2002): "Risk Aversion and Incentive Effects," *American Economic Review*, 92, 1644–1655.

KÜBLER, D., AND G. WEIZSÄCKER (2004): "Limited Depth of Reasoning and Failure of Cascade Formation in the Laboratory," *Review of Economic Studies*, 71, 425–442.

METZ, C. (2002): "Private and Public Information in Self-Fulfilling Currency Crises," *Journal of Economics*, 76, 65–85.

MORRIS, S., AND H. S. SHIN (1998): "Unique Equilibrium in a Model of Self-Fulfilling Currency Attacks," *American Economic Review*, 88, 587–597.

——— (1999): "A Theory on the Onset of Currency Attacks," in *The Asian Financial Crisis*: *Causes*, *Contagion and Consequences*, ed. by P.-R. Agenor, M. Miller, D. Vines, and A. Weber. Cambridge, U.K.: Cambridge University Press, 230–255.

——— (2002): "Global Games: Theory and Applications," in *Advances in Economics and Econometrics*, *the Eighth World Congress*, ed. by M. Dewatripont, L. Hansen, and S. Turnovsky. Cambridge, U.K.: Cambridge University Press, 56–114.

NAGEL, R. (1995): "Unraveling in Guessing Games: An Experimental Study," *American Economic Review*, 85, 1313–1326.

OBSTFELD, M. (1996): "Models of Currency Crisis with Self-Fulfilling Features," *European Economic Review*, 40, 1037–1047.

PRATI, A., AND M. SBRACIA (2002): "Currency Crises and Uncertainty about Fundamentals," IMF Working Paper WP 02/03.

SMITH, V. L. (1991): "Experimental Economics: Behavioral Lessons for Microeconomic Theory and Policy," in *Papers in Experimental Economics*, ed. by V. L. Smith. Cambridge, U.K.: Cambridge University Press, 802–812.

STAHL, D. O., AND P. W. WILSON (1994): "Experimental Evidence on Players' Models of Other Players," *Journal of Economic Behavior and Organization*, 25, 309–327.

VAN HUYCK, J. B., R. C. BATTAGLIO, AND R. O. BEIL (1990): "Tacit Coordination Games, Strategic Uncertainty, and Coordination Failure," *American Economic Review*, 80, 234–248.

——— (1991): "Strategic Uncertainty, Equilibrium Selection, and Coordination Failure in Average Opinion Games," *Quarterly Journal of Economics*, 106, 885–910.