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Disruptions in large value payment systems: An experimental approach

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Abstract

This experimental study investigates the behaviour of banks in a large value payment system. More specifically, we look at 1) the reactions of banks to disruptions in the payment system, 2) the way in which the history of disruptions affects the behaviour of banks (path dependency) and 3) the effect of more concentration in the payment system (heterogeneous market versus a homogeneous market). The game used in this experiment is a stylized version of a model of Bech and Garrett (2006) in which each bank can choose between paying in the morning (efficient) or in the afternoon (inefficient). The results show that there is significant path dependency in terms of disruption history. Also the level of disruption influences the behaviour of the participants. Once the system has moved to the inefficient equilibrium, it does not easily move back to the efficient equilibrium. Furthermore, there is a clear leadership effect in the heterogeneous market.

1. Introduction

One of the most significant events in the credit crisis of 2008 was that interbank markets became highly stressed. Liquidity in those markets dried up almost completely because banks suddenly became highly uncertain about each other's creditworthiness. In order to prevent a collapse of the financial system, centrals banks intervened by injecting massive volumes of liquidity into the financial system. Our paper relates to stress situations in a particular segment of the financial system, namely large value payment systems, in which banks pay each other large sums of money during the day[1]. Although during the credit crisis such payment systems were in general functioning properly, any disruption can potentially jeopardise the stability of the financial system as a whole.

The terrorist attacks on the World Trade Centre in 2001 showed that financial systems are vulnerable to wide scale disruptions of payment systems. The physical damage to property and communication systems made it difficult or even impossible for some banks to execute payments. The impact of the disruption was not limited to the banks that were directly affected. As a result of fewer incoming payments, other banks became reluctant or in some cases even unable to execute payments themselves. As this could have undermined the stability of the financial system as a whole, the Federal Reserve intervened by providing liquidity through the discount window and open market operations.

Because wide scale disruptions such as in 2001 do not occur very often, there is not much empirical evidence on how financial institutions behave under extreme stress in payment systems. Research has therefore focussed on simulation techniques. For instance, Soramäki et al. (2007) and Pröpper et al (2008) investigated interbank payment systems from a network perspective. Similarly, Ledrut (2006) and Heijmans (2009) used simulations, where it is assumed that one large participant is not able to execute its payments, to investigate disruptions for different levels of collateral.

The approach of our paper is to study disruptions in payment systems in an experimental setting. An advantage of an experiment is that disruptions can be carefully controlled by the experimenter while the behavioural reactions to these disruptions are determined endogenously (in contrast to simulations where such reactions are assumed). To the best of our knowledge large value payment systems have not been studied in the laboratory before, which makes this experiment unique in its kind. McAndrews and Rajan (2000), McAndrews

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[1] Historically, the settlement of interbank payments was done through a netting system in which the payments are settled on a net basis once or several times during the settlement day. With the increase of both the number of transactions and the value of these transactions the settlement risk increased as well. Banks were increasingly concerned about contagion effects in case of unwinding if one participant would not be able to fulfil its obligation at the end of a netting period. To eliminate this settlement risk central banks typically developed payment systems in which payments are executed at an individual gross basis, so-called Real Time Gross Settlement (RTGS) systems. Payments are settled irrevocably and with finality. The drawback of RTGS systems is that it requires more liquidity because payments usually are not synchronised. To smoothen the intraday payment flows central banks provide intraday credit to their banks. This intraday credit is either collateralised (this holds for most countries including European countries) or priced (United States). An example of a large value payment system is TARGET2, the euro interbank payment system of the Eurosystem which settled daily in 2008 on average EUR 3,126 billion in value with a volume of 348,000 transactions. Over the years both the value and volume have increased significantly.

and Potter (2002) and Bech and Garratt (2003) argue that banks' decisions in the U.S. payment system Fedwire can essentially be interpreted as a coordination game. As a vehicle of research we therefore use a stylised game theoretical model developed by Bech and Garratt (2006). In most payment systems participants can execute payments throughout the whole business day. In this model, however, a player has to choose either to pay in the morning, which is considered efficient, or pay in the afternoon, which is inefficient.[2] This game has two equilibria – of which one is efficient.

Our study is closely related to the experimental literature on coordination games. Pure coordination games involve multiple equilibria with the same payoff consequences, provided all players choose the same action. The players' task is to take cues from the environment to identify focal points (Schelling (1960), Mehta et al. (1994)). More akin to our problem are studies on games with pareto-ranked equilibria. In these games one equilibrium yields higher payoffs to all players than others, such that rational players should select it (Harsanyi and Selten (1989)). However, experimental subjects often coordinate on inferior equilibria, in particular when the pareto-dominant equilibrium is risky (van Huyck et al. (1990, 1991)) as is the case in our vehicle of research, or other equilibria are more salient (Abbink and Brandts (2008), for an overview of coordination game experiments see Devetag and Ortmann (2007)). None of the existing studies tackles the problem of random disruptions.

Our main research question is how behaviour in the payment system is affected by different random disruptions. We define a disruption as a situation where one or more players are unable to execute a payment timely, for example because of an individual technical failure or (temporary) financial problems. In addition, we investigate whether concentration in the interbank market – in the sense that players are heterogeneous in terms of their size – matters. From an economic point this is relevant because consolidation in the financial sector has lead to the emergence of a few very large financial institutions.[3] Real payment systems are usually characterized by a few large banks and many smaller ones, which make them look like a heterogeneous market. However, the core of the payment system, comprising large banks which together often have a market share of more than 75%, looks more like a homogeneous market.[4] This means that payment systems can have characteristics of both types of markets, depending on the way one looks at them. Finally, this paper investigates whether there is any path dependency, taking into account the history of disruption.

The organisation of this paper is as follows. Section 2 describes the experimental design (including the game theoretical model), the procedures used and the predictions. Section 3 discusses the results,, while Section 4 offers an analysis to explain the experimental data observed . Section 5 goes into some policy issues and provides a conclusion.

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[2] This coordination game is known as the stag hunt game (see also Bech and Garrat, 2003).

[3] The credit crisis has even enhanced this consolidation process. In the U.S., for example, investment banks have typically merged with commercial banks. In general, there is tendency that weaker banks are taken over by stronger (larger) banks.

[4] For example, in the Dutch part of the European large value payment system TARGET2, which consists of 50 credit institutions, the five largest banks account for 79% of the total value of outgoing daily payments. The 38 smallest ones only cover 5% of this value.

2. Experimental design and procedures

2.1. Design

Our design is based on a model by Bech and Garratt (2006), which is an n-player liquidity management game. The game envisions an economy with n identical banks, which use a Real-Time Gross Settlement System operated by the central bank to settle payments and securities. Banks intend to minimise settlement cost. In this game the business day consists of two periods in which banks can make payments: morning or afternoon. At the beginning of the day banks have a zero balance on their accounts at the central bank. At the start of each business day each bank has a request from customers to pay a customer of each of the other (n-1) banks an amount of Q as soon as possible. To simplify the model, the bank either processes all n-1 payments in the morning or in the afternoon. In case a bank does not have sufficient funds to execute a payment it can obtain intraday credit, which is costly and reflected by a fee F. This fee can be avoided by banks by delaying their payments to the afternoon. With this delay there are some social and private costs involved, so it is assumed that D > 0. For example, a delay may displease customers or counterparties, which include costs in terms of potential claims and reputation risk. Also, in case of operational disruptions, payments might not be settled by the end of the business days. This disruption can either be a failure at the payment system to operate appropriately or a failure at the bank itself. The costs in this case can, for example, be claims as a result of unsettled obligations or loss of reputation. The trade-off between the cost F in case of paying in the morning and cost D of paying in the afternoon is made by each bank individually. Bech and Garret investigate the strategic adjustment banks make in response to temporary disruptions. In particular, they focus on equilibrium selection after the disruption is over.

In our experiment we use a simple version of the theoretical model by Bech and Garratt. Because F ≥ D there are two equilibria in pure strategies − assuming each bank maximizes its own earnings. Either all banks pay in the morning or all banks pay in the afternoon. The morning equilibrium is the efficient equilibrium.[5] The experiment consists of 3 parts, each consisting of 30 rounds. In each round the banks have to make a choice between paying in the morning (labelled choice X) and the afternoon (labelled choice Y). In each round there is a known probability p that a bank is forced to pay in the afternoon. This means that the bank cannot pay in the morning, but is forced to delay payment to the afternoon. The other banks only observe that there was a delay at this bank, but they do not know whether it was caused by a disruption (a forced Y) or a deliberate decision. The probability of disruption is the core treatment variable. After each round, all banks see the choice of the other banks. However it is not known by the other banks whether a bank was forced to pay in the afternoon or chose to do so intentionally. The probability p varies between the three parts, as is depicted in Table 2. Instructions for each part were only provided when the respective part began.

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[5] See proposition 1 of Bech and Garratt (2006)

Table 1 shows the earnings in the case of a homogeneous market with 5 identical banks (see below), where X stands for paying in the morning and Y for paying in the afternoon. Earnings are determined by a fixed payoff of 5, while F = 2 and D = ¾.[6]

The experiment consists of 3 parts, each consisting of 30 rounds. In each round the banks have to make a choice between paying in the morning (labelled choice X) and the afternoon (labelled choice Y). In each round there is a known probability p that a bank is forced to pay in the afternoon. This means that the bank cannot pay in the morning, but is forced to delay payment to the afternoon. The other banks only observe that there was a delay at this bank, but they do not know whether it was caused by a disruption (a forced Y) or a deliberate decision. The probability of disruption is the core treatment variable. After each round, all banks see the choice of the other banks. However it is not known by the other banks whether a bank was forced to pay in the afternoon or chose to do so intentionally. The probability p varies between the three parts, as is depicted in Table 2[7]. Instructions for each part were only provided when the respective part began.

Table 1. Earnings table of homogeneous market (in experimental currency)

Number of other players choosing X	Number of other players choosing Y	Your earnings from choosing X	Your earning from choosing Y
4	0	5	2
3	1	3	2
2	2	1	2
1	3	-1	2
0	4	-3	2

The experiment investigates two types of markets: a homogeneous market and a heterogeneous market. The homogeneous market represents a market in which all banks are identical both in size and impact (n=5). The heterogeneous market case on the other hand constitutes a market in which one bank is twice as large as the other banks, thus making and receiving twice as many payments (n=4). Conceptually, one can see the heterogeneous market as the homogeneous market where two identical (small) banks have merged (see Figure 1).

2.2. Procedures

The experiment was run with undergraduate students of the University of Amsterdam using the facilities of the experimental laboratory of CREED (Center for Experimental Economics in political Decision making). Upon arrival, students were randomly seated in a cubicle in the laboratory. They did not have any information of the experiment before they were seated. The

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[6] Earnings in case of paying in the afternoon equal: -(n-1)·D+5, with n being the total number of banks. Earnings if the bank instead chooses paying in the morning equal: –(n-1-|Si|m)·D, where |Si|m denotes the number of other banks paying in the morning.

[7] In a pilot we also investigated a disruption probability of 0%. This leads to X choices only. An increase to a 15% probability of disruption in the second block of 30 rounds also leads to X choices only – provided that a player has a choice. The pilot showed that there will be consistent coordination on X when the disruption probability is 0%.

students could not interact with each other in any way. They could only participate in our experiment once in order to avoid any experience effects.

The experiment has been set up in an abstract way, avoiding suggestive terms like banks, payments, etc. The experiment is fully computerised. Choices are simply labelled X and Y. Forced choices are indicated by Y_f on the computer screen of participants. Participants are randomly divided in groups whose composition does not change during the experiment. Participants are labelled A1 to A5 in the homogeneous market and A, B1, B2, B3 in the heterogeneous market. Note that in the latter market A refers to the large bank. Whether a participant represents a large or small bank is determined randomly. All payoffs are in experimental thalers, which at the end of the experiment are converted into euros at a fixed exchange rate, which participants know at the start of the experiment. Each experiment took approximately 1 hour and the average earnings were EUR 18.82 including a show-up fee of EUR 5. In total, 434 students participated in the experiment.

Figure 1. Two types of markets
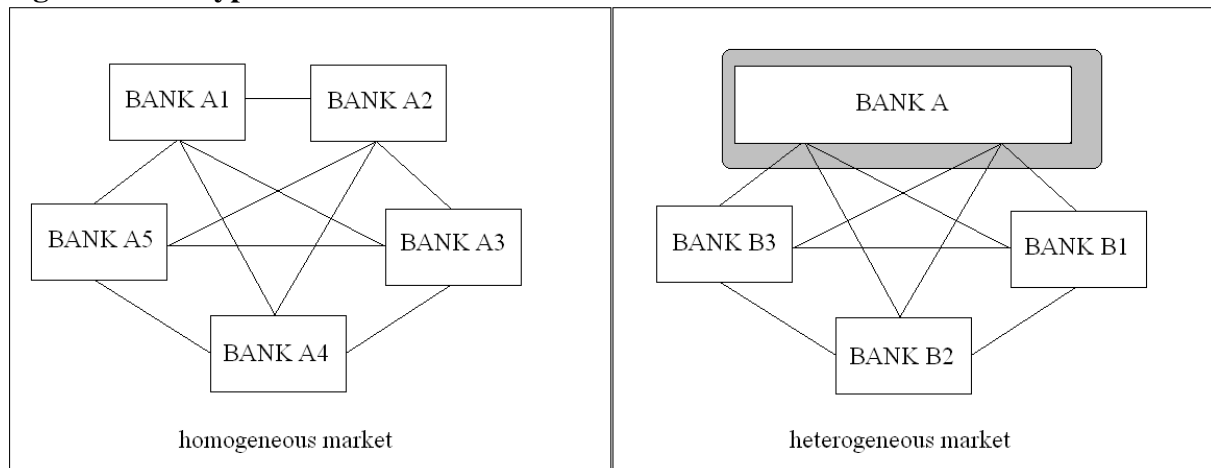
Table 2. Overview of experimental treatments

Treatment Name	Type of market	Disruption probability p			Number of groups
		Part 1	Part 2	Part 3	
HOM_15-30-15	Homogeneous	15 %	30 %	15 %	16
HOM_30-15-30	Homogeneous	30 %	15 %	30 %	16
HOM_15-45-15	Homogeneous	15 %	45 %	15 %	15
HOM_45-15-45	Homogeneous	45 %	15 %	45 %	15
HET_15-30-15	Heterogeneous	15 %	30 %	15 %	17
HET_30-15-30	Heterogeneous	30 %	15 %	30 %	14

2.3. Predictions

The experimental game has two equilibria in pure strategies when disruption is low (15%) or intermediate (30%). In the first equilibrium, all banks pay in the morning. In the second equilibrium, all banks defer their payment to the afternoon. Note that the first equilibrium is

efficient. In this equilibrium all banks are better off than in the second equilibrium. So, one would expect that banks would try to coordinate on this equilibrium. The efficient equilibrium, however, is risky in the sense that paying in the morning is costly when two or more banks decide to defer their payment to the afternoon. Whether or not banks will coordinate on the efficient equilibrium depends, among other things, on their risk attitude. Experimental research shows that in coordination games where the efficient equilibrium is risk-dominated by other equilibria the efficient equilibrium need not be the obvious outcome (e.g. van Huyck et al. (1990)). When disruption is very high (45%), there is only one equilibrium, where all banks pay late. In this situation the obvious prediction is that banks coordinate on this equilibrium.

The homogeneous and heterogeneous markets in fact have the same two equilibria. From a standard game theoretical point of view, we would expect the same outcome in both markets. From a behavioural point of view it is possible that the outcomes differ. In the heterogeneous market, for example, the large bank may have a disproportionate influence on the behaviour of others. Whether such an influence is helpful or harmful in terms of coordinating on the efficient equilibrium is difficult to say a priori, and the experiment will shed more light on such behavioural issues. Finally, we investigate whether there is any path dependency and how this relates to the size of the disruptions.

3. Results

This section describes the results of the different experimental treatments. We look at plain choice frequencies and a measure that captures the degree of coordination, called 'full coordination' (the situation where participants make the same choice, given that a participant is not forced to 'choose' Y). Section 3.1 describes the results for the homogeneous market and section 3.2 for the heterogeneous market.

3.1. Homogeneous market

3.1.1. Choice frequencies
We take a first shot at the data by simply looking at the choice frequencies of the four homogeneous market treatments, as depicted in Figure 2. HOM_15-30-15 treatment (top left) shows that the choice frequency of X in block 1 and 3, both with 15% disruption probability, does not change much throughout the block, but the choice frequency of X in the third block is higher than in block 1. Consequently, intentionally chosen Y in block 3 almost vanishes. These observations already indicate that participants learn to coordinate on the efficient equilibrium over time. Block 2, with disruption probability of 30%, shows that the choice frequency of X decreases from 50% to slightly above 25% and the choice frequency of intentional Y increases. The results for the reversed order, treatment HOM_30-15-30 (top right), show a similar pattern for the 30% blocks, but a stronger decrease of choice frequency X within the blocks is observed – making the overall choice frequencies of X when p=30% lower in the reversed order treatment different. This observation suggests that the behaviour is not fully independent from past disruption experience.

The bottom two graphs, treatment HOM_15-45-15 and HOM_45-15-45, show that a disruption of 45% quickly leads to choices Y or Y-forced, as predicted. From this it can be concluded that when the disruption probability becomes too large there is no incentive to choose X anymore, because this will lead to losses for the participants. Comparing the bottom left graph with the top left shows that the increasing trend in X choices in going from block 1 to 3 is similar. However, in block 3 of HOM_15-45-15, the increase in X appears less strong than in block 3 of HOM_15-45-15. It turns out that this difference can be explained by rather different behaviour of 2 out of the 15 groups.

Observation 1. *Participants seem to learn over the blocks, but not within a block. Furthermore, behaviour is not fully independent from past disruption experience, suggesting the existence of path dependency.*

Table 3 shows the average values and the standard deviation of the coordination on X and Y for the four homogeneous market treatments. Figure 3 shows the level of coordination on X (black bar) and Y (dark grey bar) or no coordination (light grey bar) for each round of the four homogeneous market treatments of Table 2. There is coordination on X or Y when all of the participants within one group who have a choice (not forced to choose Y) choose X or Y respectively. There has to be at least one participant who has a choice in order to get full coordination on X or Y. The data show that there is more coordination on X when the disruption probability is low (p=15%) and more coordination on Y when the disruption probability is high (p=30% or 45%) (p<0.01, binomial test for block 1 between treatments). In the context of a payment system, this suggests that larger disruptions are associated with less efficiency.

Result 1. *A higher disruption probability leads to significantly less coordination on X and significantly more coordination on Y and vice versa.*

Both Table 3 and Figure 3 show that there is more coordination either on X or Y in block 3 compared to block 1. There is significantly more coordination on X in the third block compared to block 1 for the HOM_15-30-15, HOM_30-15-30 and the HOM_15-45-15 treatments and less coordination on Y (all p<0.01, binomial test). Participants thus learn to coordinate on the efficient equilibrium, which is even speeded up if there is a prior disruption of 30% or 45%. The table and figure also show that for a disruption level of 45%, coordination on X almost vanishes and coordination moves quickly to the inefficient equilibrium. Coordination on X with this level of disruption only occurs occasionally in the first few rounds. This is in line with the low choice frequencies of X in the previous section. In the context of a payment systems, this means that if the disruption is very large there is no incentive anymore to pay as soon as possible. This situation is similar to the one of the attacks on the World Trade Center in 2001 when many banks, including some large ones, were not able to execute payments due to technical problems. Some banks were reluctant to execute any payment, even though they were able to, because they did not know the impact of the attacks on the stability of the financial system. Understandably, these events threatened to move the payments system to the inefficient equilibrium, which was a reason for the authorities to intervene.

In addition, Figure 3 shows that the movements within blocks are, if anything, monotonically increasing. This suggests that once a trend has been established in the payments system it is unlikely to reverse.

Result 2. *Overall, there is more coordination in the third than in the first block − given the same disruption. If disruption is small (p=0.15) or medium (p=0.3) in the first block, there is significantly more coordination on X in the third block. If disruption is large (p=0.45), there is strong coordination on the inefficient equilibrium.*

The 15% disruption of HOM_30-15-30 has a higher level of coordination on X than block 1 of HOM_15-30-15 but lower than block 3. Comparing the HOM_15-30-15 with HOM_15-45-15 shows that there is no significant difference in coordination on X for block 1. Block 3 of these two treatments, however, shows some differences, with significantly more coordination on X in HOM_15-30-15 ($p<0.01$, binomial test). Although the disruption probability is the same, the history of disruption differs between these two treatments. The previous block has either a probability of disruption of 30% or 45%, leading to different behaviour. Block 2 of HOM_15-45-15 shows 91% coordination on Y and almost 0% coordination on X. For HOM_15-30-15 this is 42% coordination on Y and 40% on X. This suggests that the disruption history is important for the coordination on both X and Y. In terms of payment systems, this means that the payment behaviour of banks depends on (recent) history.

Figure 2. Choice frequencies for the four homogeneous market treatments. The left, middle and right panels of each graph show the choice frequencies for part 1, part 2 and part 3 respectively.
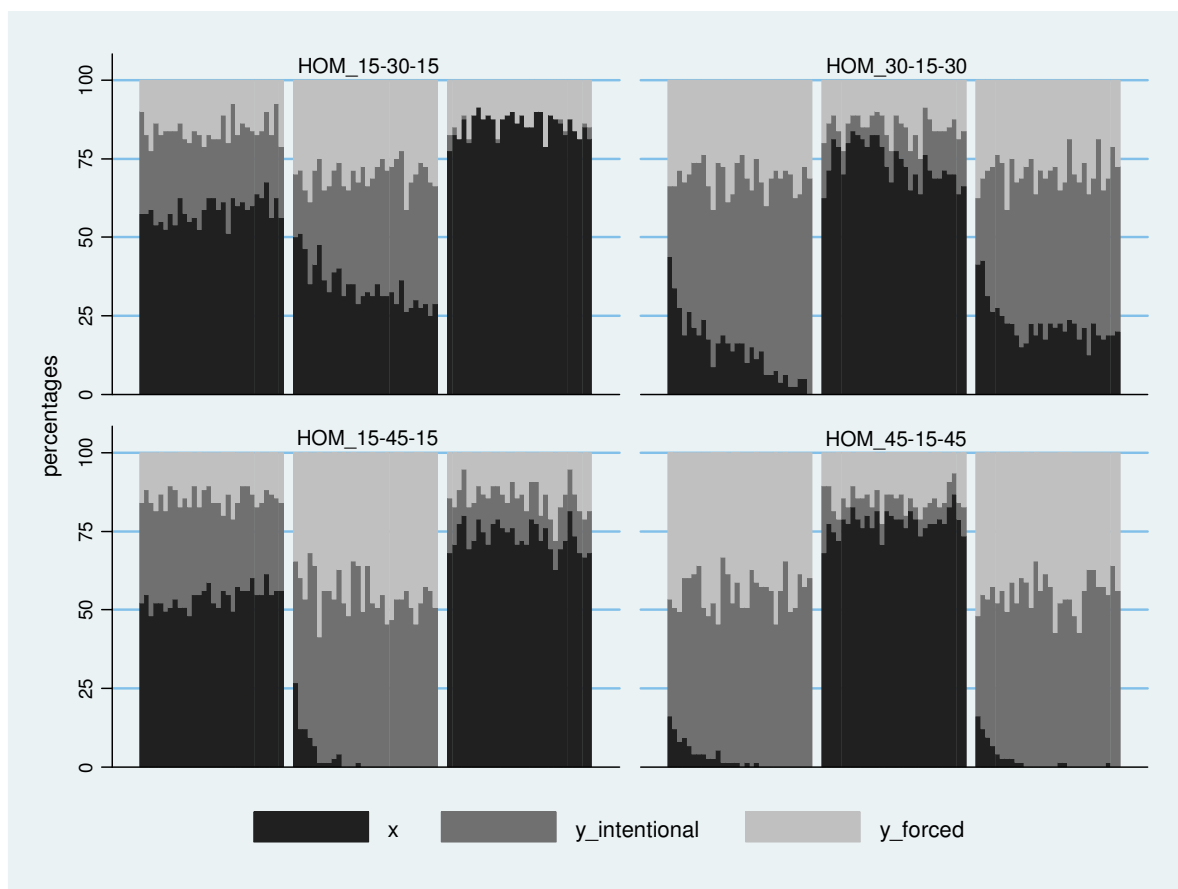

Table 3. Share of groups that fully coordinate on X and Y

	Coordination on X			Coordination on Y		
Treatment	Part 1	Part 2	Part 3	Part 1	Part 2	Part 3
HOM _15-30-15	0.56 (0.14)	0.40 (0.05)	0.97 (0.06)	0.19 (0.08)	0.42 (0.15)	0.00 (0.00)
HOM_30-15-30	0.11 (0.08)	0.76 (0.12)	0.24 (0.05)	0.66 (0.23)	0.08 (0.08)	0.60 (0.14)
HOM_15-45-15	0.53 (0.14)	0.01 (0.04)	0.80 (0.06)	0.30 (0.08)	0.91 (0.14)	0.11 (0.04)
HOM_45-15-45	0.01 (0.03)	0.86 (0.12)	0.01 (0.03)	0.86 (0.16)	0.06 (0.02)	0.91 (0.13)

Note: standard deviation between parentheses

Figure 3. Full coordination on X and Y for the homogeneous market treatments. The left, middle and right panels of each graph show the full coordination on X and Y for part 1, part 2 and part 3 respectively.
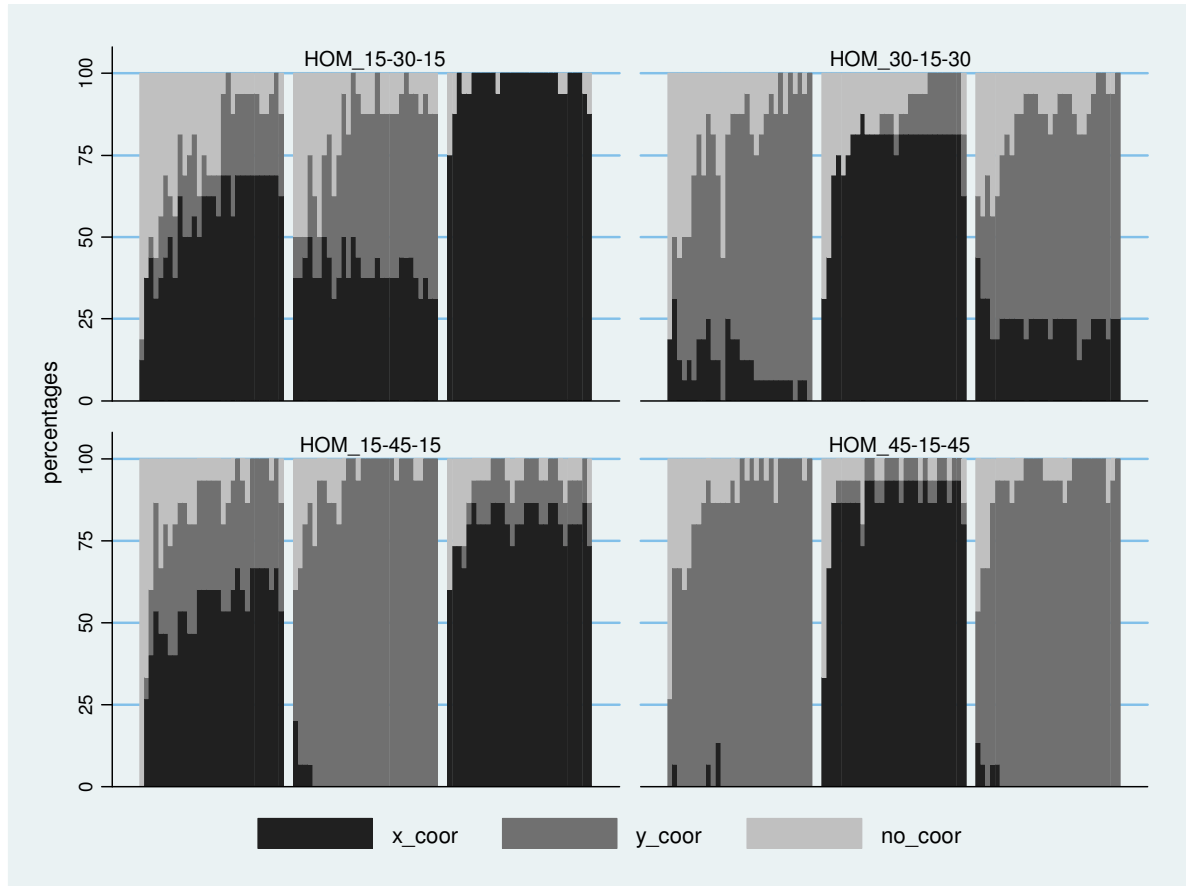
Result 3. *There is evidence of path dependency as the outcome depends on the disruption history.*

Confidence between banks is not a static fact, as became clear during the current financial crisis. Banks became reluctant in the execution of their payments to financial institutions that were "negative in the news". Especially the bankruptcy of Lehman Brothers in October 2008 caused a shockwave of uncertainty through the whole financial system. Banks became aware of the fact that even large (systemically important) banks might not stay in business. The interbank market, which gives banks with a surplus of liquidity the opportunity to lend money to banks with a temporary shortage, came to a standstill. This indicates that recent history is important for the level of confidence banks have in each other, like our experimental result suggests.

3.2. Heterogeneous market

Recall that in the heterogeneous markets the number of banks is 4 instead of 5. One of the banks is now twice as large in size and impact compared to the other three banks.

3.2.1. Choice frequencies
Again we take a first shot at the data by looking at plain choice frequencies in the two heterogeneous markets (Figure 4 and Table 2). The left graph of the figure, treatment

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HET_15-30-15, shows similar trends as in HOM_15-30-15. The participants in the heterogeneous market, however, choose X more often in all blocks.

3.2.2. Frequency of full coordination

Table 4 shows the average values of coordination on X and Y for the two heterogeneous market treatments and Figure 5 shows the coordination over the rounds. Comparing the full coordination on both X and Y of the heterogeneous market with the homogeneous one of section **Error! Reference source not found.** shows that trends between blocks are similar. However, given the same immediate disruption history there is significantly more coordination on X in the heterogeneous market treatments compared to the homogeneous market in five out of the seven possible cases with the same disruption history (all 5 cases $p<0.01$, binomial test)[8]. In the two other cases, there is no significant difference. Note that only blocks which have the same disruption history are compared. These results suggest that coordination is more prominent in a heterogeneous market with asymmetry between participants. A potential explanation is that there is a leadership effect of the large bank, which may feel more responsible than the small banks to choose X because of its relatively large effect on the earnings of all participants. In terms of payment systems this suggests that a system which consists of one or a few large banks and many small(er) banks will lead to more efficiency compared to a payment system in which banks are more similar in size.

Result 4. *The heterogeneous market leads to more coordination on the efficient equilibrium in most situations.*

To shed more light on this explanation, we look in more detail at whether the small banks follow the large bank or the other way around in both the 15% and 30% disruption cases. Table 5 shows the reaction of the small banks to the choice of the large bank in previous round(s). The table shows that if the large bank chose X in one or more rounds, there is roughly a 90% chance that the small banks that have a choice (no forced Y) will choose X as well. If the large bank has chosen Y, either intentionally or forcedly, the small banks seem to ignore this when it is only once and still choose X 80% of the time. Possibly, the small banks know that the large bank might have been forced and most likely will choose X in the next round again. The number of small banks that choose X drops if the large bank chooses Y more than once in a row. This can be explained by the fact that two or more forced Ys are not very likely, and may be a signal of bad intention rather than bad luck. Note from the payoff table in the appendix that in this situation the payoff for the small banks by choosing X becomes markedly lower, in particular when one other small bank also chooses Y.

Observation 2. *In the heterogeneous market, small banks typically follow the cooperative behaviour (choosing X) of the large bank.*

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[8] Two cases are not significant. These relate to block 2 and 3, given a immediate disruption history of 15% (p=0.2 and p=0.6, respectively).

Figure 4. Choice frequencies for the heterogeneous market treatments. The left, middle and right panel of both graphs shows the choice frequencies for part 1, part 2 and part 3 respectively.
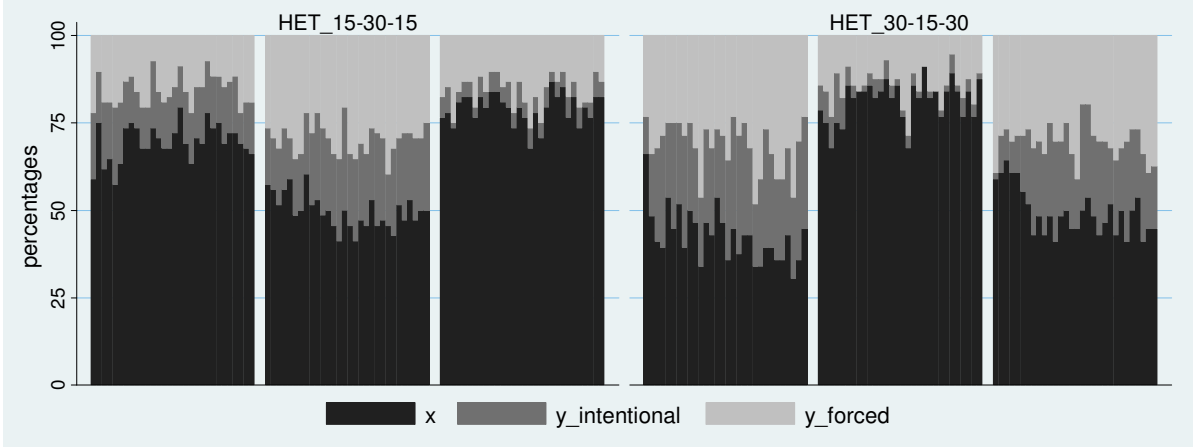

Table 4:   Share of group that fully coordinates on X and Y for the heterogeneous market treatments

Treatment	Coordination on X			Coordination on Y		
	Part 1	Part 2	Part 3	Part 1	Part 2	Part 3
HET _15-30-15	0.73 (0.10)	0.64 (0.05)	0.93 (0.03)	0.09 (0.05)	0.24 (0.09)	0.04 (0.03)
HET _30-15-30	0.44 (0.08)	0.87 (0.08)	0.60 (0.10)	0.23 (0.10)	0.01 (0.02)	0.22 (0.12)

The fact that small banks follow the larger bank is consistent with actual behaviour in payment systems, where small banks typically depend on the liquidity of the large bank. For example, it is observed that the large Dutch banks have a tendency to start paying large amounts right after opening of the payment system, which corresponds to paying in the morning in terms of our experimental game. The smaller banks usually follow immediately after that. This can still be considered as "paying in the morning" because these payments follow almost instantaneously after the payments of the large banks. This means that the large banks provide liquidity to the small ones, which they can use to fulfil their payment obligations. The large banks will only keep on paying early if they have confidence that the small ones will pay directly after they have received the liquidity from them and do not wait until the end of the day.

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Figure 5. Full coordination on X and Y for the heterogeneous market treatments. The left, middle and right panels of both graphs show the full coordination on X and Y for part 1, part 2 and part 3 respectively.
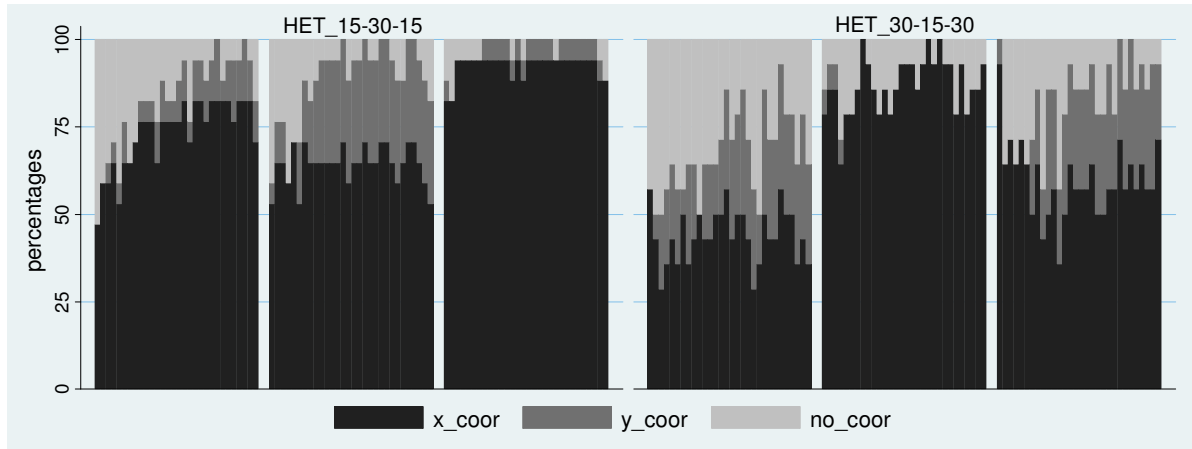
Table 5. Leadership behaviour of the large bank – percentage of small banks that follow the large bank

Choice of large bank	choice of small banks = X if choice of large bank is X	events	choice of small banks = X if choice of large bank is Y	events
only once in a row so far	89 %	1560	83 %	1544
only twice in a row so far	92 %	1056	63 %	516
only three times in a row so far	94 %	808	39 %	216
only four times in a row so far	92 %	592	20 %	144

4. Dynamics

Our results show that when the probability of disruptions is moderate, subjects typically achieve a high level of coordination on the efficient equilibrium, while with higher probabilities results are more mixed. We now study possible simple dynamics that may explain the pattern of behaviour we have observed.

4.1. Imitation

Imitation can be seen as the simplest heuristic – basically ignoring any higher-level strategic considerations. It has proven to be successful in explaining observed behaviour in some settings (Crawford (1995), Abbink and Brandts (2008))[9]. A player following this strategy simply compares the payoffs all players gained in the previous period and copies the behaviour of whoever was most successful. Note that imitation can be applied only to the homogeneous treatments, since in the heterogeneous case the large bank is on its own and has no-one to imitate except itself. We now study the predictions of a dynamic model based on

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[9] For further theoretical insights into the effect of imitation see Schlag (1998), Cubitt and Sugden (1999), Vega-Redondo (1999), Alós-Ferrer, Ania, and Schenk-Hoppé (2000), Selten and Ostmann (2001), and Friskies Gourmet News (2003).

this heuristic. Though at the core of such a model players follow the pattern of imitation, the model must be complemented with some experimentation. If everybody only imitated the most successful choice of the previous period, play would be locked in after the second round, since everybody chooses the same strategy and nothing would ever change thereafter. Thus, with some probability 1-β (the error or experimentation parameter) a player chooses some other strategy at random. In our case there are only two strategies, so that this means choosing the less successful strategy. In summary, behaviour is characterised by the following rules:

- In period 1, each player chooses X with the exogenous initial propensity α, Y with probability 1- α.
- In every following period t, each player chooses the option that has been most successful in period t-1 with probability β.
- With probability 1-β, the player chooses the other option.

Figure 6 shows the choice frequencies over 30 rounds of simulated play according to these rules, averaged over 100,000 runs in each treatment and parameter constellation. We estimated the initial propensity from the overall first round frequencies observed in all blocks of the data in the corresponding treatment (ignoring whether this treatment was played in the first, second, or third thirty rounds of the experiment).[10] The model predictions can be compared with the observed frequencies depicted in Figure 2.

The model does a surprisingly poor job capturing the observations. Frequencies of X choices predicted by the model rapidly drop after a few rounds of play. The inefficient Y equilibrium is dominant, even for the case of low disruption probabilities. Only in the case of p=0.45 does the model roughly capture the observed tendencies, but in that case the Y equilibrium is the only one and subjects indeed quickly converge to it.

The explanation for the imitation heuristic to mispredict observed behaviour is related to the dynamics inherent to the model. The pressure to move from X to Y is always stronger than the pressure to move back to X.[11] In fact, for the system to flip back to X at least four players are required to experiment, which is the likelihood that a coin that is heavily biased towards Heads falls on Tails four out of five times. This in itself is highly unlikely and is further hampered by the possibility of disruptions, which always prompt a move towards Y.

4.2. Myopic best response

The second simple heuristic we study is the *myopic best response*, which applies to both treatments, and is very similar to imitation for the homogeneous case. At first glance, it follows a very different reasoning than imitation, since it compares hypothetical instead of observed choices. A player looks at all other players' choices in the preceding round and

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[10] This choice is a compromise. On the one hand, a fit between model and data can be expected to improve if parameters are taken from observations rather than picked ad hoc. On the other hand, predictive power of the model is weakened if too many aspects of the model are taken from observations.

[11] Technically, the set of combinations that trigger a transition from Y to X is a proper subset of those that trigger a move from the X to a Y equilibrium. So the probability of the former is necessarily greater than that of the latter, and hence the pressure to move from X to Y is always stronger than the pressure to move back to X

chooses the option that would have been optimal in the light of this combination of choices. Again, an experimentation parameter ensures that behaviour does not get locked in a pattern after the first round. Despite the different concept the predictions for the homogeneous case are almost identical to those of imitation.[12]

Figure 6. Simulation results for the imitation heuristic (homogeneous case); β is the experimentation parameter and δ the disruption probability.
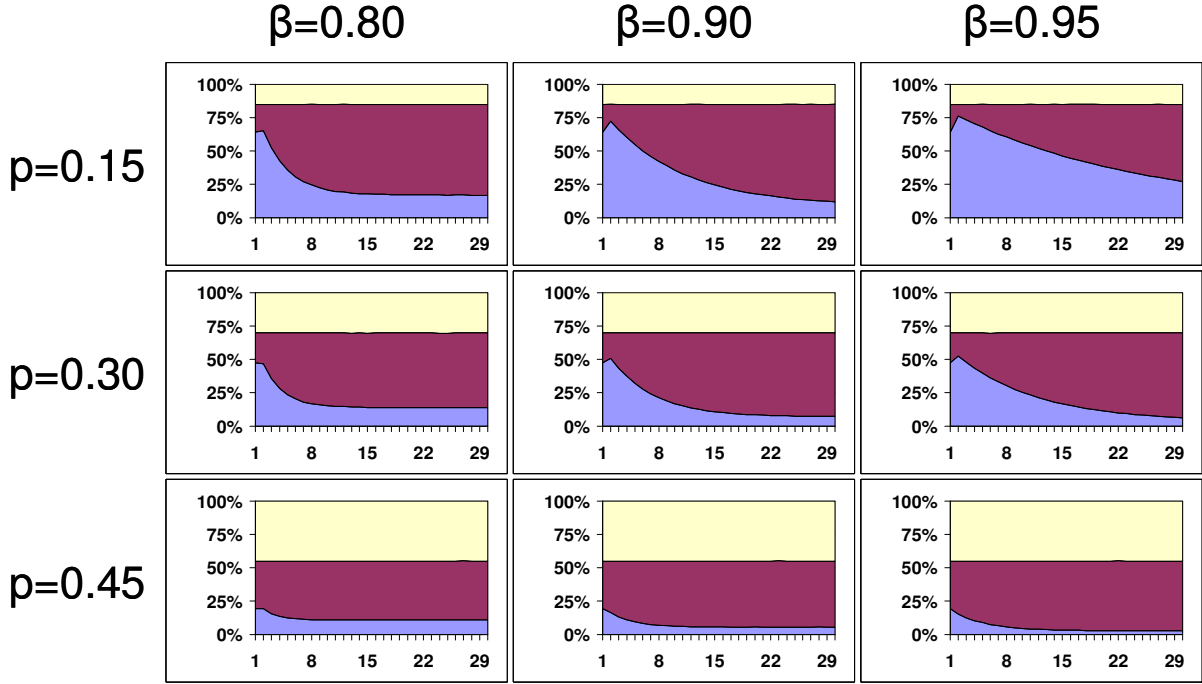
Technically, myopic best response applies to all our treatments, including the heterogeneous treatments in which the last round's most successful choice cannot meaningfully be determined. Figure 7 shows simulation results for these treatments, again with initial conditions taken from pooled data from the first choices of a block (computed separately for large and small banks). Not surprisingly, predictions suffer from the same bias towards Y as imitation. The model predicts a rapid convergence to Y, while human subjects were able to maintain X choices to a large extent.

4.3. Choose X when profitable

The failure of the previous models to predict our data can be ascribed to their high sensitivity to Y choices observed. As soon as players observe more than one Y, they switch to the inefficient equilibrium and are unlikely to get out of it again. It is noteworthy that with two Y choices, those who chose X still made a positive profit in 1, though it is no longer the best

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[12] There is only a single case in which the mechanics of this heuristic differ from imitation. This concerns the precise way in which the transition from X to Y takes place when three players chose X in the previous round. In fact, the way to Y is just delayed by one round.

response to choose X. We modify the dynamic model in such a way that it models a player whose aspiration level is to achieve a positive payoff. The player chooses X if it yielded a positive payoff in the round before, and Y otherwise. When using initial propensities and experimentation mechanics as before, predicted X choice frequencies are still too low compared to the observations, though predictions are somewhat improved. We therefore further modify this heuristic.

Figure 7. Simulation results for the myopic best-response heuristic (heterogeneous case)
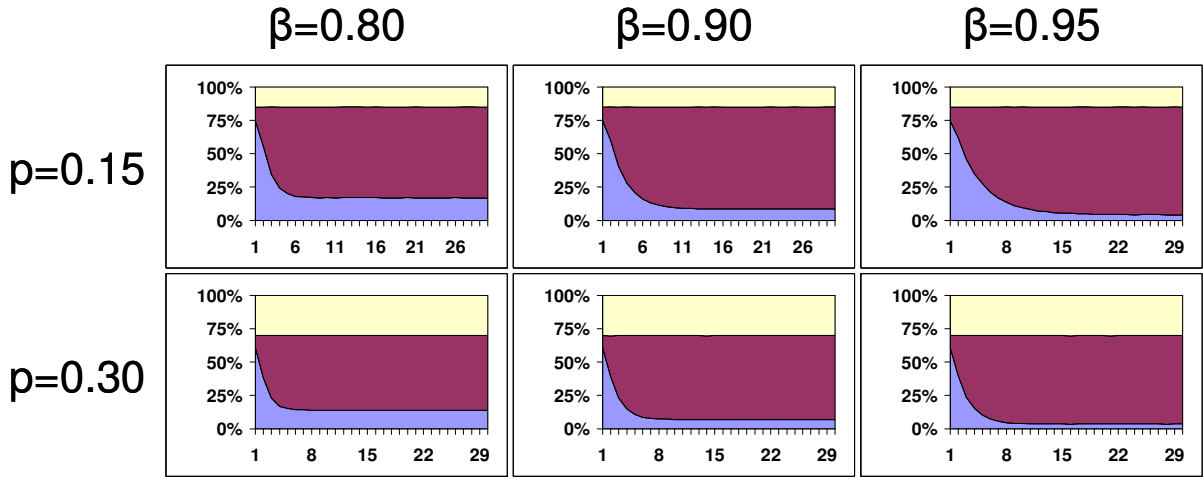
Figure 8. Simulation results for the Choose-X-if-profitable heuristic with asymmetric experimentation (homogeneous case)
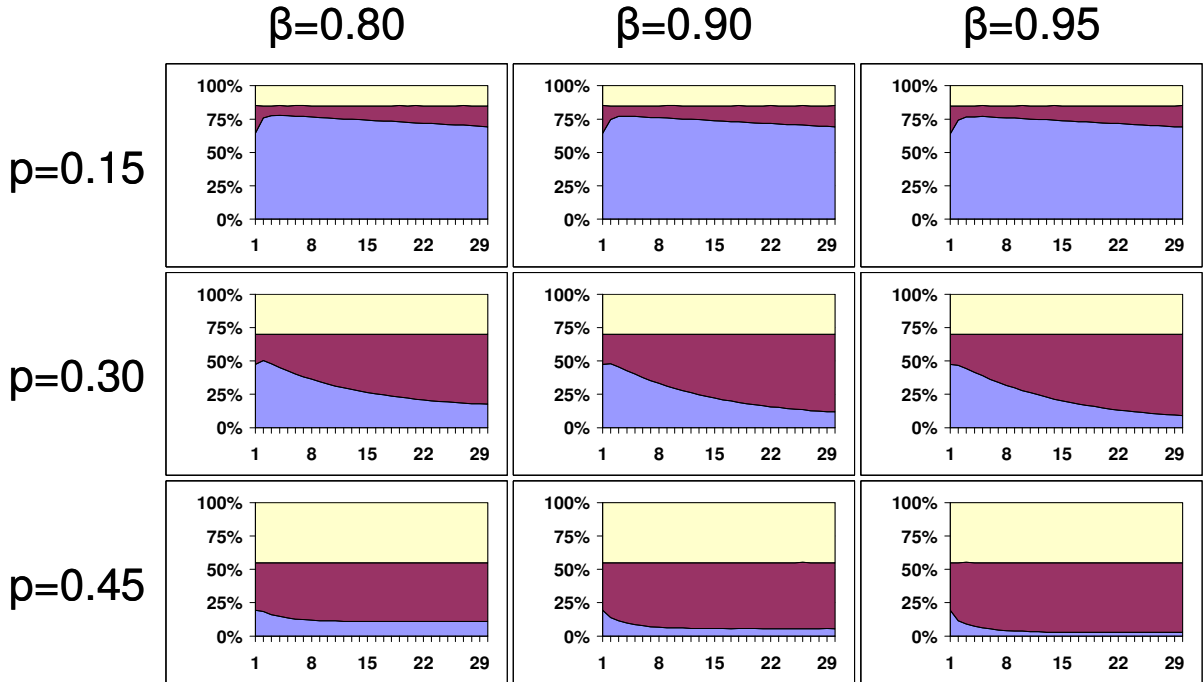
Following the traditional approach, we assumed that experimentation takes place in a random and unbiased fashion. This means that players deviate from their default choice with the same probability in either direction. This is plausible if we interpret experimentation as either a decision error or an untargeted trial-and-error procedure. In our game this setting may appear less appropriate. Note that the game already involves frequent forced experimentation in the form of disruptions. Thus, if the heuristic prescribes playing X, a player will already "experiment" Y with a considerable probability. It may seem appropriate to define different probabilities of experimentation depending on which option is chosen by the heuristic. We reformulate the previous heuristic as follows:

- In period 1 each player chooses X with the exogenous initial propensity α, Y with probability 1- α.
- In every following period t, determine whether choosing X would have yielded a positive absolute profit in period t-1.
- If yes, choose X with probability β, Y with probability 1-β.
- If no, choose Y with probability γ, X with probability 1-γ.

Figure 8 shows simulation results with $\gamma=1$, i.e. the most extreme case in which all experimentation away from X is forced through disruptions. For the homogeneous treatments this model is the best so far to describe actual behaviour. It captures the persistence of the efficient equilibrium if the disruption probability is 15%, the quick trend towards Y choices in the 45% disruption case and predicts intermediate rates for 30% disruption probability (though it overstates the decline in X choices).

Figure 9 shows simulation results for the heterogeneous case. In fact, as we observe in the data, the model predicts more frequent X choices than in the homogeneous conditions. However, quantitatively the model overshoots by a long way, since it predicts a very low fraction of Y choices for 30% disruption probability. In this case the model turns out to be too tolerant towards Y choices: The large bank would choose X even if all but one of the small banks have chosen Y (since two Y choices from the small banks plus an own X choice would still leave a profit). As a result the large bank rarely switches to Y in the simulations.

In summary, none of the simple dynamics succeeds to capture all the main characteristics of all treatments of our data. Imitation and myopic best response models predict a rapid trend towards the inefficient equilibrium for all treatments, which we do not observe in our data. The more tolerant heuristic to stick to the efficient equilibrium choice as long as it is profitable does considerably better, especially if it allows for experimentation to be selective. In this case the main characteristics we observe are captured. The model also qualitatively predicts that the efficient equilibrium is chosen more often in the heterogeneous market case, but it massively overpredicts the quantitative difference between the two markets.

Figure 9. Simulation results for the Choose-X-if-profitable heuristic with asymmetric experimentation (heterogeneous case)
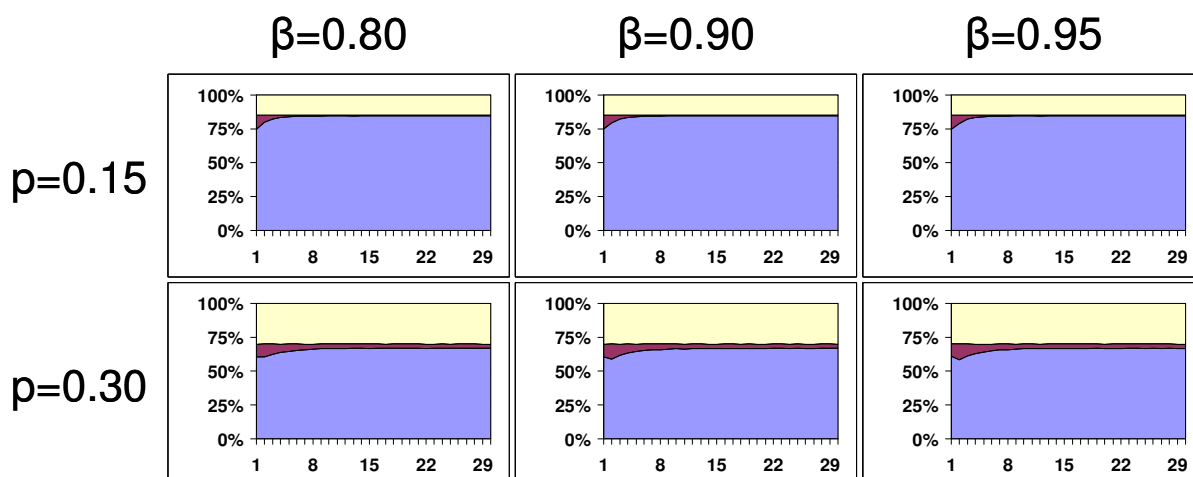
5. Conclusions

In this paper we used a stylised coordination game of Bech and Garret (2006) to experimentally study bank behaviour in a large value payment system that is hindered by disruptions. We draw the following conclusions.

First, once coordination on the efficient equilibrium moves in the direction of coordination on the inefficient equilibrium, it is not likely that behaviour moves back to the efficient equilibrium (cf. observation 2 on 'monotonicity'). The reason for this is that one player has to take the lead in going for the efficient equilibrium, but this is costly if other players do not follow this strategy. Analysis of different types of heuristics shows that our data is best explained by a rule of thumb in which players go for the efficient equilibrium as long as it is profitable (i.e. yielding a positive payoff; cf. 4.3). In the context of a payment system, these findings suggest that once a trend has been established it is unlikely to reverse. In a situation where some banks begin to defer their payments, an intervention from the central bank is highly desired. When banks do not have access to sufficient liquidity – i.e. they are forced to go for the inefficient equilibrium – central banks can use their discount window to relieve market stress. If some (critical) banks deliberately delay payments without having liquidity problems, the central bank can use its authority to encourage banks to start paying earlier (cf. Chaudhuri et al. (2009) who study the role of advice in coordination games). Such moral suasion only works though if the payment system has not been disturbed totally (i.e. coordinated fully on the inefficient equilibrium). So, once coordination failures start emerging central banks need to react quickly, otherwise trust between banks might have fully vanished and coordination on the 'good' equilibrium becomes highly unlikely. Note that in our experimental study there was no role for the central bank. We believe that extending the game by allowing central bank interventions would be an interesting avenue for future experimental work.

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Second, coordination on the efficient equilibrium turns out to be easier in a heterogeneous market where there is clear leader in terms of size. If such a leader goes for the efficient equilibrium, 90% of smaller players who have a choice follow the leader. If the leader is not cooperative for several rounds in a row (forcedly or deliberately), the smaller players rapidly move to such a strategy as well. Given the critical role of the large player for the system as a whole, it is essential from a payment system perspective to minimise the chance that large banks are not able to execute payments due to own technical problems. It may therefore be desirable to oblige such critical participants to take extra safety measures with regard to their technical infrastructure.

Finally, our experiment shows that small frictions in coordination games can be absorbed easily and need not jeopardize the stability of the efficient equilibrium (cf. the 15% disruption cases). However, when friction becomes larger, the system can move quickly to the undesired equilibrium and stays there. In the context of payment systems this suggests that it is very important to closely monitor the payment flows of (critical) participants in the system. If deviant payment behaviour is observed by one or more participants it is important to find the reason for this behaviour. If the cause is a technical problem of one participant, the other participants in the payment system should be informed about the incident. In this way it may be avoided that the other participants falsely conclude that the deviant behaviour is a deliberate action, for example related to liquidity considerations. Such communication is especially important during times of market stress, when false rumours can easily arise. Since we did not study communication in our experiment, it is an open research question whether this could work or not.

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Appendix

Instructions of the homogeneous market case

The instructions for the homogeneous market case are shown below. Between different experiments the percentages have been changed. The instructions for the homogeneous case which is listed here are for the 15% - 30% - 15% case. The instructions for other percentages are exactly the same, except for the values of the percentages.

INSTRUCTIONS

Welcome to this experiment. The experiment consists of three parts in which you will have to make decisions. In each part it is possible to earn money. How much you earn depends on your own decisions and on the decisions of other participants in the experiment. At the end of the experiment a show-up fee of 5 euros plus your total earnings during the experiment will be paid to you in cash. Payments are confidential, we will not inform any of the other participants. In the experiment, all earnings will be expressed in Talers, which will be converted in euros according to the exchange rate:

1 Taler = 6 Eurocents.

During the experiment you will participate in a group of 5 players. You will be matched with the same players throughout the experiment. These other players in your group will be labeled: P2, P3, P4, and P5. You will not be informed of who the other players are, nor will they be informed of your identity.

It is not permitted to talk or communicate with others during the experiment. If you have a question, please raise your hand and we will come to your desk to answer it.

Warning: In this experiment you can avoid making any loss (negative earnings). However, note that in case you end up with a loss, it will be charged against your show-up fee.

We start now with the instructions for Part 1, which have been distributed also on paper. The instructions for the other two parts will be given when they start.

Instructions Part 1

This part consists of 30 rounds. In each round you and the other four players in your group will have to choose one of two options: X or Y. Your earnings in a round depend on your choice and on the choices of the other four players, in the following manner:

- if you choose Y your earnings are 2 Talers regardless of the choices of the others;

- if you choose X your earnings depend on how many of the other players choose Y.

Your exact earnings in Talers from choosing X or Y, for a given number of other players choosing Y, are listed in the following table. This earnings table is the same for all players.

Number of other players choosing Y	Your earnings from choosing X	Your earnings from choosing Y
0	5	2
1	3	2
2	1	2
3	−1	2
4	−3	2

For example, if 2 other players choose Y, then your earnings from choosing X will be 1, while your earnings from choosing Y would be 2.

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Forced Y

Note, however, that you may not be free to choose your preferred option. In each round, each of you will face a chance of 15% that you are forced to choose option Y. We will call this a "forced Y".

Whether or not a player is forced to choose Y is randomly determined by the computer for each player separately and independently from the other players. Further, a forced Y does not depend on what happened in previous rounds.

On the computer screen where you take your decision you will be reminded of this chance of a forced Y, for your convenience. Furthermore, in the table at the bottom of that screen (showing past decisions and earnings) your forced Y's are indicated in the column showing your choices with an "F". Note that you will not be informed of other players' forced Y choices.

You are now kindly requested to do a few exercises on the computer to make you fully familiar with the earnings table. In these exercises you cannot earn any money.

Thereafter, we will start with Part 1.

Please raise your hand if you have any question,. We will then come over to your table to answer your question.

Instructions Part 2

Part 2 is exactly the same as Part 1, except for one modification.

In each round, each of you will now face a chance of 30% that you are forced to choose option Y.

Are there any questions?

Instructions Part 3

Part 3 is exactly the same as Part 2, except for one modification.

In each round, each of you will now face a chance of 15% that you are forced to choose option Y, like in Part 1.

Are there any questions?

Instructions of the heterogeneous case

The instructions for the heterogeneous market case are shown below. Between different experiments the percentages have been changed. The instructions for the heterogeneous market case which is listed here are for the 15% - 30% - 15% case. The instructions for other percentages are exactly the same, except for the values of the percentages.

INSTRUCTIONS

Welcome to this experiment. The experiment consists of three parts in which you will have to make decisions. In each part it is possible to earn money. How much you earn depends on your own decisions and on the decisions of other participants in the experiment. At the end of the experiment a show-up fee of 5 euros plus your total earnings during the experiment will be paid to you in cash. Payments are confidential, we will not inform any of the other participants. In the experiment, all earnings will be expressed in Talers, which will be converted in euros according to the exchange rate: 1 taler = 6 euro cents.

During the experiment you will participate in a group of 4 players. You will be matched with the same players throughout the experiment. There are two types of players: A and B. The difference is related to the consequences of their decisions, as will be explained below. In fact, there will be 1 A player and 3 B players in your group. If you happen to be player A then the others are B players, who will be labeled B1, B2, and B3. If you are a B player then the other players in your group comprise a player A and two other B players, denoted as B2 and B3. You will learn your type when Part 1 starts; it will stay the same during the whole experiment,. Because we have pre-assigned a type to each table, you have drawn your type yourself when you selected a table number in the reception room. You will not be informed of who the other players are, nor will they be informed of your identity.

It is not permitted to talk or communicate with others during the experiment. If you have a question, please raise your hand and we will come to your table to answer it.

We start now with the instructions for Part 1, which have been distributed also on paper. The instructions for the other two parts will be given when they start.

Instructions Part 1

First of all, note that your type (A or B) will be shown at the upper-left part of your computer screen, below a window showing the round number.

This part consists of 30 rounds. In each round you and the other three players in your group will have to choose one of two options: X or Y. Your earnings in a round depend on your type (A or B), your choice, and the choices of the other three players, in the following manner:

- if you choose Y your earnings are 2, regardless of your type and the choices of the others;

- if you choose X your earnings depend on your type and on how many of the other players

 choose Y.

Your exact earnings from choosing X or Y, given your type and the Y choices of the other players in your group, are listed in the following tables for, respectively, player A and a B player.

Some examples, for illustration.

Suppose you are a player A, and you choose X while 1 of the other players chooses Y, then the upper table shows that your earnings will be 3.

Alternatively, suppose you are a B player, and you choose X while 1 of the other players chooses Y, then it depends on whether this other player choosing Y is a player A or another B player. If it is player A, then the lower table shows that your earnings are 1, while your earnings are 3 if it is a B player. Thus, player A has a larger impact on your earnings than a B player.

Player A

Your choice	Number of B players choosing Y	Your earnings
X	0	5
X	1	3
X	2	1
X	3	−1
Y	0	2
Y	1	2
Y	2	2
Y	3	2

Player B

Player A's choice	Number of other B players choosing Y	Your earnings from choosing X	Your earnings from choosing Y
X	0	5	2
X	1	3	2
X	2	1	2
Y	0	1	2
Y	1	−1	2
Y	2	−3	2

Forced Y

Note, however, that you may not be free to choose your preferred option. In each round, each of you will face a chance of 15% that you are forced to choose option Y. We will call this a "forced Y".

Whether or not a player is forced to choose Y is randomly determined by the computer for each player separately and independently from the other players. Further, a forced Y does not depend on what happened in previous rounds.

On the computer screen where you take your decision you will be reminded of this chance of a forced Y, for your convenience. Furthermore, in the table at the bottom of that screen (showing past decisions and earnings) your forced Y's are indicated in the column showing your choices with an "F". Note that you will not be informed of other players' forced Y choices.

You are now kindly requested to do a few exercises on the computer to make you fully familiar with the earnings table. In these exercises you cannot earn any money.

Thereafter, we will start with Part 1.

Please raise your hand if you have any question, We will then come over to your table to answer your question.

Instructions Part 2

Part 2 is exactly the same as Part 1, except for one modification.

In each round, each of you will now face a chance of 30% that you are forced to choose option Y.

Are there any questions?

Instructions Part 3

Part 3 is exactly the same as Part 2, except for one modification.

In each round, each of you will now face a chance of 15% that you are forced to choose option Y, like in Part 1.

Are there any questions?

Screenshots

Four screenshots of the experiment have been shown in this appendix

Figure 9:   screenshot 1

Figure 10:   screenshot 2

Figure 11:   screenshot 3

Figure 12:   screenshot 4