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Switching Behavior:
An Experimental Approach to Equilibrium Selection

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Abstract

The aim of this thesis is to investigate experimentally the reliability of the predictions of evolutionary game theory concerning equilibrium selection. Particularly, I analyze how an adjustment of the initial conditions, which were stated to be one of the essential factors in determining long-run stochastic equilibrium, may change the outcome of the game.

The current work studies equilibrium selection in the framework of technology adoption in the presence of an established convention. It consists of three chapters. The first provides an extensive survey of theoretical and experimental literature on equilibrium selection, technology adoption and the emergence of conventions. The second chapter presents an experiment that investigates whether a new technology, represented by an introduction of either a risk-dominant or a payoff-dominant strategy, is capable to break a conventional equilibrium and provoke the adoption of another one. In the third chapter I present an experiment that studies whether adding a dominated strategy to a coordination game facilitates transition from one equilibrium to another by changing their basins of attraction.

Keywords: Equilibrium selection, Technology adoption, Convention, Evolutionary games, Basins of attraction.

JEL Classification: C72, C92, D85, O30

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Introduction

Coordination problems arise in every area of social life. Typical examples include speaking the same language, paying with the same currency or using the same technology. In fact, adherence to a common standard by itself serves as a coordination device (Schelling, 1960; Lewis 1969). Usually, originated from a historical accident, a regularity that successfully resolved a coordination problem in the past becomes a conventional form of behavior (Lewis, 1969). Adherence to a convention recognizable by all the members of a society promotes people's mutually profitable and consistent behavior.

In this work, I study coordination as people's ability to collectively adopt the same strategy in a technology adoption game, which makes it a case study for two laboratory experiments. Experiments on technology adoption are not very common in the literature. Most of them deal with very simple coordination games that are common in similar experiments on the more general problem of coordination failures. The main point of this thesis is that the literature has so far missed a crucial point in the technology adoption process: technologies hit the market at different points in time. It is rarely the case that all technologies are simultaneously available for the consumers to choose. Rather, in many cases, when a new technological standard appears it has to displace an existing standard that dominates the market. Familiar examples are paper latters that were replaced with emails; CD replaced LP records, and eventually replaced by mp3s; floppy disks that are replaced with USBs and other technology innovations.

My research deals with this problem by devising a slightly more complex setting to analyze the emergence and the replacements of technological standards.

My experiment involves pre-coordination on the incumbent technologies and later the introduction of a new one. This design illustrates several factors that determine the success or failure in the transition from one technology to another. First, it allows us to investigate the importance of the strength of the existing standard (as measured, for example, by the popularity within a certain population) in making it more difficult the transition to a new (and superior) technology. Second, it sheds light on the question of whether a transition from one standard to another is more likely to take place when the new technology is compatible with the existing one, or it is Pareto superior. In the game theory parlance, this amounts to investigate the classical question of the relative importance of risk-dominance vs. Pareto efficiency in equilibrium selection. This part of the thesis can be seen as a contribution to the experimental literature on noisy equilibrium selection processes first studied in Kandori, Mailath and Rob (1993).

Chapter 1 of the thesis starts with a survey of the literature on equilibrium selection: it presents an analysis of evolutionary games and their origins, reviews deterministic and stochastic models of equilibrium selection, describes particularities of global and local matching networks, reports the results of the most prominent experiments in this field. Later in this chapter I revise theoretical and experimental studies on technological adoption, including explanations of such notions as “lock-in”, “critical mass”, “path-dependence” and others. The chapter finishes with the section, which reviews theoretical and experimental works that analyze how an adherence to an existing convention may influence people’s coordination behavior and, consequently, impact the long-run equilibrium selection.

The experiment presented in the Chapter 2 aims to resolves the ambiguity of the results among the experimental literature on coordination games surveyed in

Chapter 1. The classical stochastic models of equilibrium selection (Kandori, Mailath and Rob, 1993 - henceforth KMR; Young, 1993; Ellison, 1993) argue that in 2x2 co-ordination games the risk-dominant equilibrium is the most likely result of equilibrium selection in the long run. However, several experimental studies provide evidence that in the lab the most frequent equilibrium is the efficient one (Corbae and Duffy, 2008; Cassar, 2007). My work contributes to this literature by devising an original method of testing the theoretical predictions of the stochastic models. In the KMR model (1993) the key element is represented by the ease with which a population of myopic agents switch from one equilibrium to another. For example, in a 2x2 coordination game the population will spend most of the time at the risk-dominant equilibrium because it is the equilibrium, which is most difficult to escape through a series of "mistakes". Notice however, that the theory does say nothing about the initial condition of the selection dynamics. If players are initially prone to play the Pareto efficient equilibrium, that equilibrium will be more likely to select in the few rounds of an experiment. An accurate test of the predictions of the KMR model should then involve at least two elements. First, it is a study of probability of transitions from one equilibrium to another. In particular, it should test whether it is easier to move from the Pareto efficient to the risk dominant or vice versa. Second, it should incorporate "noise", in the form of individual mistakes in decision making, because the transitions across equilibria are generated by the mistakes made by the individuals.

The experiment presented in the Chapter 2 evaluates the predictions of the KMR by paying attention to these two fundamental points. The first element is that the population is first lead to select one equilibrium, so that an experimentalist has control over the initial condition. Then a new strategy is added to the game in order to produce a new Nash equilibrium. My aim is to see whether we observe a transition to the new equilibrium or not, and whether this transition depends on the properties of the new Nash equilibrium. Concretely, the properties of the new strategy are chosen so to transform the equilibrium selected during the pre-play rounds into a risk-dominant or a Pareto-dominant equilibrium. My experiment aims is to show whether a transition is more or less likely depending on the nature of the new strategy we introduce.

Transitions are unlikely in the absence of noise, especially in the small time span of the typical equilibrium. To get round this problem I changed the traditional way in which coordination games are played in two crucial ways. First: we replaced familiar labels like “A” and “B” with more neutral labels such as “$” and “@”. Second, I switched the order of the strategies in the matrix the subject had on the screen, so that they could not reply on simple rules such as “pick the top-left strategy”. This expedient makes mistakes more likely, so that the predictions of the KMR model can be tested even in the few rounds of one experiment. The experiment has confirmed the importance of noise in the equilibrium selection process. In the pilot sessions in which strategies had non-neutral labels, coordination was easy to obtain and transitions between equilibria where extremely rare. In addition, the favored equilibrium was the Pareto efficient both in the local and in the global matching. With neutral labeling the results were markedly different. Coordination was more difficult to establish and transitions between equilibria where more likely. Finally, the experiment was run in two different settings: local and global matching, as the existing literature suggests that has a dramatic impact on the selected equilibrium. The selected equilibrium crucially depended on the matching procedure: while in the global matching setting the population’s choices confirmed the predictions of the KMR in selecting the risk-dominant equilibrium, in the local matching setting the subjects tended to select the Pareto-efficient equilibrium, independently from the initial conditions.

Chapter 3 contains a second experiment, based on the recent theoretical work by Kim and Wong (2010), in which the authors suggest that the presence of dominated strategies may affect the equilibrium that is selected by myopic agents. Classical game theory states that (iteratively) dominated strategies should not be taken into consideration when studying equilibrium selection, as common knowledge of rationality ensures that they will never be played. However, it is a well-known fact that they may play a role once we drop the assumption of common knowledge of rationality.

Kim and Wong (2010) address this issue in the framework of the stochastic process of equilibrium selection. They show that the results of the KMR model is not robust to the addition of dominated strategies, as the presence of such strategies changes the sizes of the basins of the equilibria of the game, and hence the long-run stability of the different equilibria. Their main result is that *any* Nash equilibrium of a game can be made the long-run prediction of a model in the spirit of KMR if suitably chosen dominated strategies are added to the game.

The experiment I present in the chapter 2 challenges this proposition. As in the first experiment, the game included a few pre-play rounds where the players had to choose a conventional equilibrium. After one of two equilibria had been selected, a dominated strategy was introduced to the game. Being strictly dominated, the new strategy did not add a new Nash equilibrium. Rather, it changed the basin of attraction of the existing equilibria, so to facilitate the transition from one equilibrium to another. The properties of the added strategy depended on the convergence result at the pre-play rounds: it made easier the transition to the equilibrium that was *not* selected.

The experiment has demonstrated a clear tendency of individuals to select the risk-dominant equilibrium. When the initially selected equilibrium was risk-dominant, the added strategy eased the transition to the Pareto efficient equilibrium. However, despite a few switches after the introduction of the new strategy, a successful transition was never observed. On the other hand, in the cases when the dominated strategy supported the risk-dominant equilibrium such transition was observed due to several irrational choices by the subjects. However, since the number of observations is limited these findings still require further verification.

1. Literature review

1.1 Introduction

Considerable research efforts have been made in attempt to understand the mechanisms of technology adoption in a competitive environment. However, it still remains unclear why some technological innovations quickly take root and become a part of everyday life, while others require much more time to be adopted or even utterly fail get a foothold in the market. There is a significant number of studies that analyze how technologies that remained dominant in a market for a long time delayed an adoption of innovations and locked-in their consumers (see for examples Katz and Shapiro, 1985, 1986, 1992; Farrell and Klemperer, 2007; Liebowitz and Margolis, 1994, 1995). The reason for this interest is that markets can get locked-in inefficient technologies, which with time may become a conventional standard. The presence of network effect and increasing returns to scale make this problem even more difficult to overcome since a deviation from it would result in a loss of network benefits. The established standard works as commonly known coordination device, following which enables participants of a market to profit from the joint use of a technology. Even if this standard is inferior, each member of a society chooses it as the only known way to overcome coordination failure as long as he expects all others to do the same (see Young, 1998; Bowles, 2004).

Despite a broad theoretical and empirical research in this field, the conditions at which a market tends to lock-in remain elusive. Early works on this topic suggested that lock-in is the result of path-dependency of the adoption process (David, 1985, Arthur, 1989). The authors argued that random small events at the beginning of the adoption process irreversibly determine further development path of a population of adopters. In David's words, technological adoption is a process in which "temporally remote events, including happenings dominated by chance elements rather than systematic forces" (David 1985, p. 332) determine the outcome. Arthur and David's arguments suggest that in the presence of an established standard technology, a superior innovation would not be adopted unless a transition to it is riskless.

Later, game theoretical studies revealed that the transition from the status-quo technology to a new one is strongly affected by their respective properties. These studies pointed out that compatibility among technologies is a major factor in determining the chance of such a transition, more important than efficiency. Large part of this literature was based on evolutionary models in the spirit of KMR. Besides a better understanding of the compatibility vs. efficiency issue, these models introduced a major technical innovation. In contrast to path-dependent Arthur's model (1989), these evolutionary models are based on ergodic stochastic processes, whose outcome is not determined by the initial conditions. (Young; 1993, KMR, 1993; Blume, 1993; Ellison, 1993). This approach offers a sharp prediction about equilibrium selection under the assumption that noise is arbitrary small. It suggests that, independently of the initial conditions, in the long run a population tends to converge to a single equilibrium, which is usually referred to as *stochastically stable* (Foster and Young, 1990; KMR, 1993; Young, 1993). Which equilibrium will be selected is determined by the relative sizes of all the equilibria of the game. In complex games computing the stochastically stable distribution is rather difficult. However, in two by two coordination games this approach yields a straightforward conclusion: the only stable equilibrium is the one with the largest basin of attraction. In the terminology introduced by Harshanyi and Selten (1988) evolution favors the risk-dominant rather than the efficient equilibrium (KMR, 1993).

A more nuanced picture emerged in later studies, when the structure of interaction was explicitly taken into account. For example, in local interaction structures, depending on the matching method and the network architecture, the outcome of a coordination game may be the efficient, rather than the risk-dominant equilibrium. A further refinement came from considering several revision mechanisms. The original models in the spirit of KMR (1993) were based on some variant of the so-called best-response dynamics. Agents were supposed to adopt a strategy and when given the opportunity to revise their choice they would adopt a best response to the current state of their population. Several alternatives to this revision rule were proposed. For example, Alòs-Ferrer and Weidenholzer, (2008) showed that if instead of playing a best response agents *imitated* the most successful choice, the evolutionary process may favor efficiency rather than risk-dominance.

The experimental literature revealed further elements that influenced equilibrium selection in coordination problems. Among factors that were observed to increase efficiency were: fixed matching protocol, full feedback, communication between subjects and a fewer number of players in a group (see Devetag and Ortmann, 2007 for a survey). Several experiments on evolutionary games resulted in archiving the efficient rather than the risk-dominant equilibrium (Berninghaus et al. 2002; Cassar, 2008; Hossain et al., 2009; Hossain and Morgan, 2010; Barrett et al., 2011).

Although previous research on coordination games has analyzed several aspects that influence the equilibrium selection, it omitted a serious factor that may affect dramatically the process of technology adoption. This factor is the existence of a common standard that has been established in a society before new technological achievements were developed. Several theoretical studies show how inferior cultural-institutional persistence may cause long-term economic and social effects and prevent transition to more efficient forms (Young and Burke, 2001; Acemoglu and Robenson, 2008; Nunn, 2009). Belloc and Bowles (2013) is a recent model that suggests that the transition to a superior standard depends on how rational agents are assumed to be and on the degree of the connectivity between subjects.

In the experimental literature this theme has attracted little attention. Very few works used experiments in order to explore individuals' tendency to switch away from the status-quo standard technology and to adopt a new one. Hossain and Morgan (2009) is an exception. They present an experiment in which agents always switch away from inefficient technological standards, towards more efficient ones. Keser et al. 2011 showed that these results are not robust. A new technology is more likely to be adopted if its relative payoff-dominance increases and riskiness decreases.

The present work contributes to this literature in attempting to explain how much the existence of an established standard may prevent an adoption of a new technology. Current chapter provides a literature review of the most relevant articles on three topics: equilibrium selection, technology adoption and the power of existing convention. Combination of these three areas of research performs as an able instrument in investigation of technological adoption in conditions close to natural and serves as a necessarily contribution in further experimental investigation of the problem of technological adoption. I start with an overview of the theories of equilibrium selection, discuss some stochastic best-reply models and then move to the experimental findings. In the subsequent section I analyze work that has been done in the field of technological adoption, both theoretical and experimental, particularly concentrating on the impact of network effect. Finally, in the last section, I outline the main insights in the research on conventions and their influence on people's choices reported by theoretical and experimental studies.

1.2 Equilibrium Selection in Evolutionary Games

1.2.1 Theoretical Literature on Evolutionary Games

Equilibrium selection in games with several equilibria has constituted a wide stream of literature on game theory. The most prominent example of such a game is the *Stag Hunt* coordination game, represented on the table below. We shall always assume that the game is symmetric, so that A=a, B=b and so on. The game has two strategies: to hunt a stag or to hunt a hare. If a>c and d>b both strategies profiles "Hunt Stag" and "Hunt Hare" constitute Nash equilibrium. To make this coordination game a *Stag Hunt* it is further assumed that a>d, so both player prefer the equilibrium in which both hunt a stag. However, hunting a stag is also more risky. To model this one may assume that a=1, c=0 and b=d>1/2. Hence, hunting a stag yields a positive payoff only if also the other player also hunts a stag. Hunting a Hare, on the contrary, yields a positive payoff regardless of the choice of the other. The assumption that b=d>1/2 ensures that for each player hunting a hare is a better strategy under the assumption that the other chooses among the two strategies randomly. This can be generalized relaxing the assumption that b=d to any game in which b+d>1/2 (the assumption that a=1 and b=0 is just a normalization). The stag hunt game illustrates the dilemma between an efficient, but risky, strategy and a safe but inefficient one.

	Hunt Stag	Hunt Hare
Hunt Stag	a, A	b, C
Hunt Hare	b, C	d, D

Table 1. "Stag Hunt" Game

Harsanyi and Selten (1988) were the first to introduce the concepts of risk-dominance and payoff-dominance and further provided their detailed description. They argued that in games with Pareto-ranked equilibria the inherently more reasonable equilibrium is the one that gives the highest payoff (Harsanyi and Selten, 1988, p. 88). Therefore, they suggested that the payoff-dominance is a crucial aspect in equilibrium selection that the risk-dominance attribute should be considered irrelevant in coordination games. In accordance with the rationality assumption of classical game theory, efficiency is the most reasonable selection device, and rational players guided by the principle of collective rationality should converge to the payoff-dominant equilibrium.

However, numerous theoretical works call the approach of Harsanyi and Selten (1988) into question and suggest that the coordination failure is a very likely outcome in coordination games. Later Harsanyi (1995) himself has revised his position and proposed that the risk-dominance rather than the payoff-dominance should be the main criterion of equilibrium selection.

As a way to overcome the ambiguity and the lack of definite equilibrium selection principle, researchers turned to the evolutionary game theory approach. Its technique is based on a principle of natural selection, which aids to obtain more reliable predictions and to build more realistic models. Evolutionary games consider a repeated strategic interaction between large populations of anonymous agents. Two main assumptions underlie evolutionary games: large (or infinite) uniform population of players making independent decisions and random pairwise matching. While the use of large populations comes from biological literature, in economics such practice enables applying the law of large numbers for the calculation of expected payoffs. In large populations the weight of a single individual is negligible, so the payoff of an individual is determined not directly by his own actions but by frequencies with which each strategy is executed in his population (see Vega-Redondo, 1993, 1996). Player's payoff function, his role in a game, available strategies and preferences are determined by the population that he belongs to. The second assumption of random matching leaves no possibility for local interaction between players. Agents in population games are assumed to be anonymous and identical.

1.2.1.1 Biological Origins of the Evolutionary games

A fundamental work that initiated a development of the modern evolutionary economics was research by Maynard Smith and Price (1973). Their study made a major contribution in literature through providing mathematical and biological justifications of animal behavior and evolution of a population over time. Maynard Smith and Price dropped the hypothesis of rationality, which was crucial to the classical game theory and created a framework where the only requirement for interacting agents is to execute their strategies. Maynard Smith developed a Nash equilibrium refinement called an *evolutionary stable strategy* as such a strategy that "if all the members of a population adopt it, then no mutant strategy could invade" (Maynard Smith, 1982, p.10). Evolutionary stable strategy must be effective against competitors and in the same time successful to defend itself facing other agents who perform different strategies. Maynard Smith specified two conditions for a strategy S to be evolutionary stable: either

1) E (S,S) > E(T,S), or

2) E(S,S) = E(T,S) and E(S,T) > E(T,T), for all T ≠ S;

where S and T are the strategies in the game, and E(T, S) is the expected payoff from playing strategy T against S. The first condition means that it needs to be a strict Nash equilibrium and the second condition says that if T gives the same payoff against S, then playing strategy S against strategy T must give a higher payoff than T obtains against itself. In other words, a strategy S evolutionary stable strategy if it yields a larger payoff than any other strategy T in a population in which the largest number of individuals adopt S, and there is a negligible fraction of "mutants" that use T.

The evolutionary stable strategy approach is static: it focuses on those situations in which one strategy has already been established in a population and investigates the conditions at which it remains stable. A more dynamic approach is the so-called *replicator dynamics*, originally proposed by Taylor and Jonker (1978) with the explicit purpose to provide a dynamic base for the static evolutionary stability concepts of Maynard Smith and Price (1973). The replicator dynamics is a system of differential equations that represent how population's state changes over time. Assume that the agents in a large population choose their strategies from the set $S \in \{1, \ldots, n\}$. Let x_i is be the proportion of the population that plays strategy i. The vector $x = (x_1, \ldots, x_n)^T$ is the state of the population and is an element of the simplex $\Delta = \{x \in \mathbb{R}^n : x_i \geq 0, \Sigma_i x_i = 1\}$. Let A be the (symmetric) payoff matrix of the game. Then $(Ax)_i$ is the expected payoff of an agent of type i and $x^T Ax$ is the average payoff in the state x. The replicator dynamics assumes that per capita rate of growth $\frac{\dot{x}}{x}$ is the difference between payoff of the type i agent and the average payoff in the population:

$$\dot{x}_i = x_i((xA)_i - x^T Ax)$$

The basic idea of replicator dynamics originates from biology and is characterized by a natural selection mechanism: a fraction of population that adopts a better performing strategy grows faster compared to a fraction of population that uses a worse-than-average strategy. Evolution supports high payoffs strategies and eliminates strategies with low payoffs by means of withdrawal of players who use it or induces them to switch to a more efficient strategy.

1.2.1.2 The Evolutionary Approach in Economics

In economics the evolutionary approach was mostly used as a method to overcome the problem of multiple Nash equilibria. It serves as an equilibrium selection approach that analyzes the dynamic stability of possible Nash equilibria and predicts which of them is more likely to be selected. In contrast to the assumptions of perfect rationality that characterize classical game theory (which is frequently deemed to be too demanding), the evolutionary approach assumes that the behavior of subjects is boundedly rational. This has a long tradition in economics, which predates the birth of evolutionary game theory. Friedman (1953), for instance, argued that the in economics the evolutionary pressures on firms and consumers perform to a large extent as an optimization process that determines the survival only of the fittest strategy. Subjects that survived natural selection acquire necessary skills for the required task and consequently exhibit optimal behavior, i.e, act *as if* they were rational (Friedman, 1953). In a similar vein, Alchian (1950) emphasized the role of imitation of successful actions of others as a basis of individuals' behavior. Therefore, in evolutionary economics optimal choices of individuals are not taken as chosen once and for all, but rather considered to be consequences of agents' learning and experience that takes place through time. However, if an evolutionary selection leads to a Nash equilibrium, then for the long-run settings perfectly rational and the evolutionary selected players are indistinguishable (see Weibull, 1995).

A large body of literature in game theory is concentrated on evolutionary models described by deterministic dynamics that predict history-dependent equilibrium selection (for a survey see Weilbull, 1995; Hofbauer and Sigmund, 1998; Sandholm, 2010). In such models, the equilibrium selection in games with multiple equilibria is fully determined by the initial state of the population. When the dynamics starts in the basin of attraction of a given equilibrium, that equilibrium will be selected. In the Stag hunt game, the risk-dominant equilibrium has a larger basin relatively than the payoff-dominant equilibrium. Intuitively, it is more likely to include the initial state of a population and consequently lead the population to the risk-dominant equilibrium.

This intuition can be further refined using a technique to study games with multiple Nash equilibria originally proposed by Foster and Young (1990) and usually associated to KMR. Foster and Young claimed that in evolutionary games small deviations from equilibrium are inevitable, and therefore proposed an equilibrium refinement that requires a long-run equilibrium to be resistant to such noise. Their model captured the limitations of evolutionary stable strategy concept, which did not consider multiple simultaneous mutations as a continuum of events. Stability, according to Foster and Young (1990) is based on the assumption that the mutations are not isolated events and the system does not return to the previous state before the next mutation occurs. The accumulation of small "trembles" may cause a population to switch occasionally from one equilibrium to another. One can then ask which equilibrium is more likely to observe, given that transitions from one equilibrium to another are always possible. Their definition of a stochastically stable equilibrium answers this question. According to their definition, a state P is *stochastically stable* if "in the long run, it is nearly certain that the system lies within every small neighborhood of P as the noise tends slowly to zero" (Foster and Young, 1990, p.3).

Similar to the replicator dynamics, in the Foster and Young (1990) model agents meet randomly and their payoff is measured in terms of the change in their reproductive rate. Adding mistakes to the choices of agents, the authors come up with a path-independent way to identify, which equilibrium is most likely to be selected in the long-run and which is robust to perturbations. Foster and Young (1990) emphasized the importance of small stochastic perturbations in refining the predictions of long–run behavior of individuals and clearly demonstrated how it leads population towards a particular equilibrium. Such technique was further developed in works of other researchers such as Canning (1992), KMR (1993), Blume (1993), Young (1993) and others.

Foster and Young (1990) proposed to compute stochastically stable equilibria by calculating the lowest number of mistakes needed for a transition to every equilibrium from any other. For the 2x2 Pareto-ranked games, the limit distribution is concentrated around the pure strategy risk-dominant Nash equilibrium. Thus, by incorporating noise with dynamics in one model, Young (1993) created a new, different principle of equilibrium selection, which was further elaborated by other researchers. He showed that only the risk-dominant Nash equilibrium can be the stochastically stable equilibrium. Since the risk-dominant equilibrium is resistant to mistakes, once it is achieved it will the only conventional equilibrium in the long-run.

Young (1993) expanded his previous work on stochastically stable equilibrium and developed a theory of equilibrium selection based on evolution of a conventional way of play and implemented it for repeated 2X2 coordination games within large population. In his model, two randomly picked players play a fixed coordination game. After making their choices, each player receives a feedback about the actions of his co-players and remembers it for a bounded period of time. The agents in the model are myopic best-responders: they choose a best-reply according to the distribution of strategies in their memory. Young (1993) called such process an *adaptive play*. If an equilibrium has been chosen for all the periods that agents can remember, it develops into a conventional way to play the game. Clearly, all such states are absorbing, in the sense that once a convention has been selected, no agent would choose a different action. However, if agents make mistakes – there is a small probability that they do not best-respond – such process has no absorbing states because transitions can take place, due to mutation, from any equilibrium to any other.

The concept of a stochastically stable state was also used by Kandori, Mailath and Rob (1993). Their dynamic model is focused on exploring an equilibrium selection in the long-run settings under the addition of mutations. In the KMR model (1993), each agent is playing against the whole population and receives a payoff after each round, which is equal to the average payoff in his population from executing a particular strategy. This contrasts with Young's model (1993) where agents consider their strategies according to the time averages of opponents' past play.

With a fixed high probability individuals observe the distribution of the pure strategies within their population and pick a best response to it. In coordination games this process leads the population to one of equilibria of the game. Which equilibrium is selected depends upon the basin of attraction in which the initial condition is located. Without noise, a population would remain in any equilibrium, which is selected in the first place. The resulting stochastic process is thus non-ergodic and the final distribution depends upon the initial conditions. As in the Young (1993) mode, the addition of perturbations allows transitions from one equilibrium to another. Under these conditions, the evolutionary process is described by an ergodic Markov chain, and therefore equilibrium selection does not longer depend on the initial conditions. The authors showed that with the introduction of mutations, from any starting point the system converges to a unique distribution. As the probability of mutation converges to zero the limiting distribution is determined by the number of mistakes it takes to switch from one equilibrium to another. In 2x2 coordination games, just like in the Young (1993) model, the selected equilibrium is the risk-dominant.

Subsequent research by Bergin and Lipman (1996) criticized the approach by Young (1993) and KMR (1993) saying that it is "dishearteningly nonrobust" to the mutation rate variation (Bergin and Lipman, 1996, p. 2). Bergin and Lipman (1996) proposed a model in which agents in different states made mistakes with different probability. They showed that if mistakes are state-dependent, any state may become a long-run equilibrium through manipulation of the amount of noise inherent to it. For instance, they consider a model in which agents are more likely to make a mistake when they are not satisfied with the state they are in. This would imply that the mutation rate is larger in the risk-dominant equilibrium than in the Pareto efficient one. They showed how to set the mutation parameter for each state in a way that makes the limiting distribution to put probability one on the Pareto efficient equilibrium. More in general, if the mutations are appropriately chosen, then *any* of the invariant distribution is achievable as a long-run outcome. The rather depressing conclusion is that if mutations are allowed to be state-dependent, then any Nash equilibrium can be made stochastically stable.

In a response to the work by Bergin and Lipman (1996) van Damme and Weibull (2002) developed a model with endogenous mistake probabilities. The authors assumed that agents make an effort to control their chances to make a mistake in playing a particular strategy. They modeled a game where the probability of making a mistake depends on the payoff loss due to that mistake. Intuitively, this can be explained by the assumption that players tend to experiment less in states with higher payoffs, and therefore mistakes that lead to great losses are less likely. The effort that agents make to avoid mistakes was modeled to have a disutility. The model showed that the marginal disutility needed to reduce the chance of a mistake resulted to be equal to the marginal disutility from the loss. In case when the control is effortless (has zero disutility) fully rational players do not make mistakes and choose the best-respond. In this way, Damme and Weibull (2002) vindicated the original results by Young (1993) and KMR (1993) showing that there exists a unique stochastically stable equilibrium.

1.2.1.3 Models of Local Interaction

An early critique to the equilibrium selection arguments based on "mistakes" is that a transition from one equilibrium to another is extremely unlikely since it requires a large number of simultaneous mutations. A possible answer to this criticism was provided by Ellison (1993). He discusses a variant of the KMR equilibrium selection model where the agents are arranged on a circle and interact only with *k* direct neighbors on the right and on the left (see *Figure 1*). These interaction neighborhoods overlap between agents. This kind of interaction is more plausible in those situations in which a person's social circle is limited to a few members of one's family, friends and colleagues. As other models, the local matching approach sought to find an answer which of two equilibria in a game, risk-dominant (blue) and payoff-dominant (red), will be selected. Since agents in the local matching model are myopic best-responders, transition from one equilibrium to another crucially depends on the payoff earned by the individuals who is located at the border between two clusters of individuals who play different strategies. To see this, notice that at each round any agent is equally likely to meet somebody on his right and on his left. For the individual located on a border, this translates into an equal probability of meeting a blue or a red opponent. If the game they play is a Stag Hunt game, playing the inefficient risk-dominant strategy is the best response. Notice that since this is true for every individual at a border, learning will inevitably expand the neighbors for who the risk-dominant equilibrium is selected and shrink the others.

Consider now how noise affects this model. Imagine that all individuals play the Pareto efficient equilibrium and, for ease of presentation, that they only interact with one individual on the right or on the left. Occasionally, a random mutant appears and switches to the risk-dominant strategy. Observing this and the fact of negative changes in their payoffs, if the neighbors of this mutant update their strategies, they will switch to the risk-dominant strategy since it is the only best-response. A single mutant is thus sufficient to spread contagiously the risk-dominant strategy to the entire population. Now, consider the opposite situation: all players play a risk-dominant equilibrium. Suppose, one mutant switches to the payoff-dominant strategy. His neighbors observe it but having compared the expected payoffs for both strategies from playing with their own neighbors, prefer to stay playing the risk-dominant strategy since it remains a best-response in a neighborhood in which half of the population play red, the other half play blue. Hence, a very large fraction of population is needed to in order to make others follow this rule and to adopt the payoff-dominant strategy.

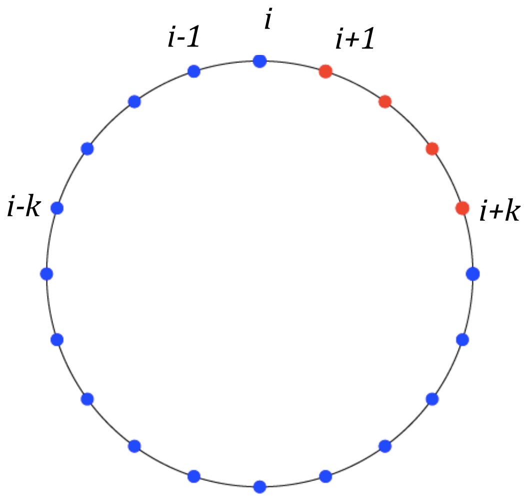

Figure 1. Circular City Model

Ellison (1993) claimed that this result remains robust also when players have more neighbors and interact on a lattice where each agent is placed on its vertices (*Figure* 2). The only difference is that in this case the waiting time of transition to the risk-dominant equilibrium increases significantly. Ellison concluded that under the best reply learning, the risk-dominant strategy is the unique long-run equilibrium in the local matching circular city model. The results of Ellison's local interaction protocol fully support the KMR's theory even though the transition mechanist is of a different nature. Ellison's circular city model showed that a risk-dominant strategy spreads in population fast and contagiously without a need for a large number of simultaneous mutations. A circle interaction model supports convergence to the risk-dominant equilibrium and maintains its power in large populations.

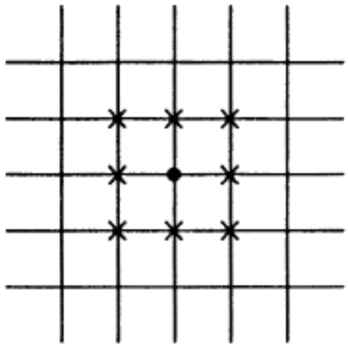

Figure 2. Interaction on a Lattice in Two Dimensions

Later Ellison (2000) provided another way to prove that an equilibrium is a stochastically stable state known as a radius-coradius theorem. The author gave a definition of a *radius* of an equilibrium as a minimum number of mutations needed to leave the basin of attraction of this particular equilibrium. The *coradius* of an equilibrium is defined as a minimal number of mutations needed to reach the basin of attraction of this equilibrium from a different equilibrium. Ellison showed that if a radius of an equilibrium exceeds its coradius this equilibrium is a unique stochastically stable state.

A recent work of Ellison, Fudenberg and Imhof (2014) studies the speed of convergence in an evolutionary model characterized by a Markov process. The authors defined convergence to be quick if the expected time to reach the state remains uniformly bounded over all the initial conditions as the number of players goes to infinity. The system is said to leave the state slowly if "the probability of getting more than ε away from [this state] in any fixed time T goes to zero as the population size increases", where ε is the probability of mutation. A convergence is fast if the expected time to reach a state is quick while the expected time for a population to leave that state is slowly. Ellison et al (2014) found that if the probability of mutation is above a certain level then the system would have fast convergence to the risk-dominant equilibrium. Otherwise, if the mutation rate is below, the system leaves slowly each equilibrium and therefore does not have fast convergence to any of them. Moreover, the authors concluded that monotonic growth of the number of players that execute risk-dominant strategy is closely related to fast convergence especially in two-actions game.

Blume (1993) presented another stochastic evolutionary model with a local interaction that supports the results of Young (1993), KMR and Ellison (1993) models. The author considered the local interaction model and distinguished two types of strategy revision: best-response and stochastic-choice. He found that the rate of convergence decreases as the interaction neighborhood grows. He concluded that both risk-dominant and payoff-dominant equilibria are possible since both of them have limits and the initial conditions fully determine the limit behavior. However the equilibrium with the largest basin of attraction, which is in general risk-dominant, is more likely to be selected.

1.2.1.4 Imitation models

The main assumption of the imitation models is that the agents, instead of playing a best response, imitate the actions of the players who earned the largest payoff in the previous round in their neighborhood. Such strategy revision protocol was proposed by Esher et al. (1998) whose model considered interactions on a circle but the authors concentrated on the Prisoner's Dilemma games though. According to their model, the efficient strategy may survive only if its executers are grouped together, so the benefits that it yields are enjoyed primarily by themselves. Although, such situation is subject to an invasion of mutants that play a strategy, which is harmful for efficient coordination.

Alos-Ferrer and Weidenholzer models (2006, 2008) studied imitation in 2×2 coordination games of different interaction structures under an addition of mutations.

The authors suggested that while for the global interaction structure the best-reply strategy mostly corresponds to the imitation one, while for the local interaction the strategy that gives the largest payoff and a best-respond may not coincide.

Alos-Ferrer and Weidenholzer (2006) demonstrated that if each player is assumed to adopt the strategy that gave the largest payoff in his neighborhood in the previous period, eventually the most efficient strategy would spread contagiously among all the players through the overlapping interaction sets. In contrast, the best-response mechanism in the circular city model would make players switch to the risk-dominant strategy. Although the speed of convergence was found to be independent of the size of a population, they showed that the long-run equilibrium selection depends on the size of interaction radius between the agents.

Alos-Ferrer and Weidenholzer (2008) considered information spillovers that arise from agents' interaction on an arbitrary network. The agents interacted directly only with their immediate neighbors, but observed the behavior of others beyond their interaction radius. Such design enabled learning from imitation of the most successful behavior in the population and resulted in efficient coordination.

In general, the authors showed that large size of interaction neighborhoods promotes convergence to the efficient equilibrium. In contrast, if each agent allocated on a circle interacts only with his immediate neighbors, the population is most likely to converge to the risk-dominant equilibrium.

In the subsequent work, Alos-Ferrer and Weidenholzer (2014) concentrated on the investigation of agents' behavior in the minimal effort games. The authors considered two different imitation techniques, which are "imitate the best" and "proportional imitation rule", which is a salience-based imitation rule. It intends that players choose strategies with probability that is proportional to the positive difference between a payoff from this strategy and players' own payoff in the previous period.

The authors concluded that independently of the interaction structure there is no hope for efficient result if information is limited to the interaction neighborhood. However, under the assumption of salience-best imitation rule and in the presence of informational spillovers between the neighborhoods, a convergence to the efficient equilibrium is possible.

Interesting outcome was obtained by Khan (2014) who studied stochastically stable behavior in 2x2 coordination games. The author considered both global and local interactions and also disentangled complete and incomplete observability. The model demonstrated that in the full observability case, the Pareto-efficient equilibrium is the stochastically stable state since the risk-dominant equilibrium is more affected by players' experimentation under the imitation rules. Under the limited observability, both game equilibria may be stochastically stable: the risk-dominant equilibrium may happen to be the most successful strategy that is observed and therefore be spread in population by imitation.

Chen et al. (2012) analyzed agents' imitation behavior in local settings in evolutionary coordination games and obtained similar results. The researchers found that both risk-dominant and Pareto-dominant equilibria may coexist in the long-run. The final convergence, according to the authors, depends on the payoffs' structure and the population size. Global interaction structure promotes faster convergence to the payoff-dominant equilibrium than the local interaction one. Moreover, authors agreed that the imitation rules is the crucial factor that determines agents' long-run behavior.

1.2.1.5 Models of Network Interaction and Local Mobility

There is a strand of the literature that investigates local interaction with in different locations. The main idea of these models is that different societies have different norms and conventions that may change over time or be adopted by different fractions of population. Taking this into consideration, researchers argued that models have to reflect these real-life situations where people have the control over their interaction structure. Therefore, researchers started to develop models where players were given a possibility to choose their location and in this way decide which strategy they want to play.

Ely (2002) and Bhaskar and Vega-Redondo (2004) questioned Ellison's (1993) assumption about the exogeneity of the neighborhood structure and showed how the possibility of choosing partners may change the result. They proposed a "migration" model where players have an opportunity to revise their strategies and locations corresponding to them in order to maximize their payoffs[1]. If agents observe that their neighbors play an inefficient strategy they may move to that part of the circle (or to an isolated "island") where a subset of players plays an efficient strategy, and hence receive a greater payoff. In this way, soon all the players abandon inefficient locations and risk-dominant locations loose its force, an efficient equilibrium becomes the only selected. These models demonstrated that the possibility to freely choose partners who play efficient strategy enables efficient coordination in a circle model. Goyal and Vega-Redondo (2000) prove a somewhat counterintuitive result: in "migration" models where the relocation is costly, the

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[1] Robson (1990) considered mutation to a different strategy as a costless signal of a player about his willing to play a more efficient strategy. In this sense, the island models are similar to the signaling ones: coordination on the more efficient equilibrium is simplified though the identification of players' intentions.

long-run equilibrium is the efficient one. If these costs were small enough the opposite is true: the risk-dominant equilibrium is selected in the long run.

Unlike random mutations evolutionary models, Oechssler (1999) developed a model where efficient convergence was reached though mobility of players between Nash equilibria in the game. His approach assumes that players who share a common convention interact more between themselves than with outsiders[2]. Therefore, the Oechssler's (1999) model included that in any period players can adjust their strategy and move to another convention that would give them a higher payoff. This design and the assumption of no mutations allows to the author to conclude that the process will always converge to an efficient equilibrium.

Schwalbe and Berninghaus (1996) constructed a model with a finite population of boundedly rational agents in order to study the effect of group interaction. Their work showed that the group size and interaction structure are influential factors of the evolutionary stability of any equilibrium. Morris (2000) adopted the same principle for his evolutionary model. He found that the maximal contagion arises as a result of low neighborhood growth and sufficiently uniform local interaction structure. A study by López-Pintado (2006) aimed to find conditions at which a new strategy may spread in a population. Assuming a myopic-best response dynamics, she found that a contagion adoption of a strategy depends on the degree of risk-dominance and the connectivity degree between agents' in the network. Author concluded that in the random networks with short average path length between players a high contagion will be expected. However, the necessary condition for the contagion to occur is the risk-dominance of the strategy.

[2] A tendency of individuals to have a higher rate of interaction with the members of their own group, kin or type is called viscosity. Such phenomenon is widely known in biology and has also been applied in other scientific areas. For more detailed information see Mayerson et al. (1991)

1.2.2 Experiments on Coordination Games

Much research has been produced on the experimental investigation of coordination games. The existing evidence is mixed. Many experiments confirmed the theoretical predictions about the convergence to the risk-dominant equilibrium (Van Huyck, Battalio, and Beil, 1990, 1991; Cooper, DeJong, Forsythe, and Ross, 1990). Others obtain convergence to the payoff-dominant outcome and find methods to increase the coordination rate on the efficient equilibrium. A critical literature survey by Devetag and Ortmann (2007) provides a comprehensive analysis of experimental investigation of coordination games and identifies the major factors that affect coordination rate in games with Pareto-ranked equilibria. Besides the difference in payoffs of the secure action relative to the risky action, among the most influencing factors that promote efficient coordination were: large number of playing rounds (Berninghaus and Ehrhart, 1998; Van Huyck, Cook and Battalio, 1997;Van Huyck et al., 2007), smaller group sizes (Van Huyck, Battalio, and Beil, 1990; Bornstein, Gneezy and Nagel, 2002; Van Huyck et al., 2007;), availability of feedback information (Berninghaus and Ehrhart, 2001).

Van Huyck et al. (1990) studied a minimum effort game, that is an extension of the stag-hunt game to multiple players. In a minimum effort game the players simultaneously choose the level of effort they want to contribute and the final payoff for each player is an increasing function of the smallest effort. The payoff function is such that all the effort levels constitute Nash equilibria and the highest effort level chosen by all players corresponds to the most efficient equilibrium. The authors observed that with repeated play and small group size, the Pareto-dominant equilibrium tended to be selected more frequently. Van Huyk et al. (1990) explained coordination failure by subjects' strategic uncertainty in their co-players' actions (see also Crawford et. al, 2008). Particularly, in their repeated interaction experiment participants were aware of the payoff-dominant action and preferred to execute the strategy corresponding to the lower effort level. As a result, the game converged to the least efficient outcome.

Crawford (1991) gave an evolutionary interpretation to the results of the experiment by Van Huyk et al. (1990). He suggested that players move away from the efficient equilibrium in order to minimize their payoff losses: a mutation to a low-effort-strategy reduces payoff of mutants less than it reduces the payoffs of the high-effort players. Given agent's beliefs, each round they adjusts their strategy, which in turn decreases the minimum of the group and affects other players' beliefs. In general, Crawford (1991) agrees with the conclusions about people's coordination behavior observed by Van Huyck et al. (1990), although he recognizes differences between learning and evolution, emphasizing history dependence.

An experiment by Barrett et al. (2011) investigated the evolution of groups' coordination in a competitive environment. The authors aimed to interpret the impact of the group structure on the emergence of coordination and the effect of the group size on the achieved level of coordination. Subjects in the experiment were asked to play a minimum effort game where agents' payoffs were represented by a function that combines individual's own choice and a minimum group value, which was announced publicly. Their experiment involved a genetic algorithm according to which the fittest group is enlarging by adding an offspring to its population at the cost of the least fit group. After reaching a certain size this group splits into two groups. Barrett's et al. (2011) experimental findings are aligned with the previous research and support the hypothesis that the achieving coordination is more problematic with the increase of the number of the participants in the game. The experiment showed that the increase in group size after a number of rounds positively affects game's convergence to the payoff-dominated equilibrium. With a large group size, more players chose the-risk dominant strategy. Nevertheless, few rounds after the split, i.e. the division of the entire group on two groups of equal size, clear evidence that players favor the payoff-dominant equilibrium was observed.

The experiments by Anderson et al. (2001) and Berninghaus, Ehrhart and Keser (1997) used evolutionary dynamics in order to investigate if participants converge to a socially efficient equilibrium in their play. Anderson et al. (2001) revisited the minimum-effort game with multiple Pareto-ranked equilibria adding noise to the game. The introduction of noise as a logistic probabilistic choice function resulted in convergence to the risk-dominant equilibrium as the noise vanishes, as predicted by the stochastic models. The main goal of the experiment by Berninghaus, Ehrhart and Keser (1997), which was run in a continuous time, was to determine the conditions under which players end up in equilibrium and to examine the role of information for equilibrium convergence. The authors compare people's behavior in two experimental settings: the first is a game with a unique socially efficient asymmetric equilibrium, the second is a game that has a Pareto-efficient state, but doesn't have a pure strategy Nash equilibria. Experimental data has shown that in the first case players spent significantly more time in or near the Pareto efficient state than in the second. The authors also found that complete information about the payoff function increases the time that subjects spend at the efficient state. Moreover, increasing players' frequency of switching strategies results in decreasing payoffs.

1.2.2.1 Experiments on Network Structure and Matching Methods

The experimental work on networks gave diverse results. The outcome of coordination games resulted to be highly sensitive to the network structure and matching method used during experiments. Keser, Ehrhart, and Berninghaus (1998) tested the impact of local-matching interaction protocol on the equilibrium selection. Using the "circular city" model in their coordination game, the authors observed that groups of eight players located on a circle converged to the risk-dominant equilibrium, thereby confirmed the theoretical prediction. In contrast, a decrease of group size to three players occurred to lead the play to the efficient equilibrium. The subsequent paper by Berninghaus, Ehrhart, and Keser (2002) generalizes these results. In particular, researchers found that in the games where the efficient Nash equilibrium is associated with a relatively small amount of risk, local interaction may lead to the Pareto-efficient outcome. The authors also compared two different architectures of local interaction and concluded that a two-dimensional lattice interaction promoted more efficient coordination than an interaction on a circle with the same number of partners. Contrary to the previous results, the later experiment also showed that in the long-run the group size had no effect on the players' choices when they are allocated on a circle.

Boun My et al. (1999) performed a coordination game experiment under global and local matching protocols. The authors investigated how the degree of risk-dominance may influence equilibrium convention, and therefore their experiment included settings with three different sizes of the basins of attraction of the risk-dominant equilibria. The authors indeed observed that the larger basin of attraction to the risk-dominant equilibrium promotes a higher rate of convergence. However, the interaction structure itself did not play a significant role for the convergence of the game: Boun My et al. (1999) did not observe more frequent convergence to the risk-dominant equilibrium in a circular city model than in the other cases.

Corbae and Duffy (2008) studied coordination in several interaction structures: global, local and “marriage” (interaction of two isolated pairs of players). The observed that in all types of network, after ten rounds the play converged to the Nash equilibrium, which was both efficient and risk-dominant. After that, the game was changed and the efficient equilibrium no longer remained risk-dominant. The authors observed that no player changed his strategy, regardless of the network. However, in another treatment they observed that if one of the players was forced to play the inefficient strategy, the local and marriage interaction structures lead to the risk-dominant equilibrium while players in the global structure remained playing the efficient equilibrium.

Cassar (2007) considered global, local and small-world networks in coordination games. The experiment consisted of eighty rounds and each network consisted of eighteen players. She observed efficient coordination in all the networks, the highest rate being the small-world network. The author concluded that the extent to which agents are connected with each other and average distance between players inherent to the “small-world” network promote coordination on the Pareto efficient equilibrium.

1.3 Technological Adoption

1.3.1 Theoretical Predictions

A large part of the literature on technological adoption, both theoretical and experimental, is concentrated on the problem of equilibrium selection in the presence of several Nash equilibria. Indeed, technology adoption and equilibrium selection are closely related, although these two researches are slightly different in focus. Technology adoption studies aim to investigate the diffusion of new technologies (in the presence of other technologies or standards) rather than the convergence to equilibrium itself. The existing models of technology adoption address disparate topics such as market environment, network effects, compatibility, switching costs, lock-in. They analyze the conditions for technological transition from a status-quo technology to a new one and emphasize the importance of established standards conventions and path-dependence processes.

The initial stimulus for this research was given by David's (1985) work on the persistence of inferior technologies, with the now classical example of the QWERTY keyboard (which will be discussed in more details in the subsequent section). Given David's observations, Arthur (1989) investigated the role of network effects for the occurrence of technological lock-in and established the mathematical foundations of path – dependence theory. In Arthur's model there are two competing technologies. Agents are assumed to have natural preferences either for one or the other. Consecutively and in random order they choose one technology to adopt. They choose their technology on the basis of their natural preferences and on the total number of agents who have already made their choices. Under the increasing returns assumption, both technologies create network effect yielding higher payoffs with greater adoption. As soon as one of the technologies accumulates more adopters than the other, all the subsequent players choose this technology and "lock into" it, although it may be against their natural (a priori) preferences. Both technologies have what Arthur calls an "absorbing barrier": the process inevitably leads population to the technology which barrier is reached first. Since players cannot reconsider their choices, the accumulation of a sufficient mass of adopters of particular technology leaded to lock-in and its complete market domination.

Arthur (1989) has discovered the importance of the “small events” that take place at the beginning of the process of technological adoption and gave the first rigorous treatment of the concept of path-dependence. His work illustrated two fundamental conditions for path – dependence to take place. . First, in game-theoretic terms, there must be several strict Nash equilibria, corresponding do different technological standards; second, the self-reinforcement dynamics of the game, which is triggered by contingent events. In this context history is important since choices of early adopters define further development path, which eventually leads to lock-in. In turn, lock-in may lead to inefficiencies and to the persistence of inferior technologies.

There are very many examples where products became market leaders not because of their advantageous properties or good performance but due to their large network of consumers. Lock-in is one of the key issues studied by network economics. Lock–in usually occurs when the production of a good or a service exhibit increasing returns to scale, which is beneficial for the supplier, but results in forcing consumers to choose a product dominant in a market almost independently of its properties. The assumption of increasing returns, necessarily for the lock-in situations, is closely related to the “critical mass” concept defined by Rogers (1962) in his study of technological adoption in the framework of sociodynamics. The critical mass is defined as the minimum proportion of the population that has adopted a particular technology needed to make all the followers benefit from choosing it. Later the concept of “critical mass” was rediscovered for economics as a threshold of population required to make a value of a good to consumers greater than its price by virtue of the network effect (see Weibull and Björnerstedt, 1993; Weibull, 1994).

Network effect plays a crucial role in studying technology adoption and subjects' attitude to changes. Many theoretical models have been developed in order to explain the impact of network effects, or network externalities, on people's decision making and in particular on their tendency to adopt new technologies. Behavioral and experimental economics put a lot of effort to explain the demand side of technological adoption and to explain from a psychological point of view how individuals perceive innovations and adopt them. A pioneer work in the field of network economics was developed by Katz and Shapiro (1985). Their concept of a network effect was basically identical to the effect of increasing returns to scale, which implies the increase of a net value of a given action if other players also take equivalent actions.

The idea that markets get locked into the first technological standard that gains a sufficient foothold has been challenged by Liebowitz and Margolis (1994). Their article shed light on the nature of technological adoption referring to the overwhelming historical evidence of repeated transitions from one technological standard to another. They cite as examples the replacement of typewriters with computers, long-play records with CD-players and later with MP3 files, VHS cassettes with DVDs. With these real-world examples Liebowitz and Margolis (1994) aimed to disprove the theory of David (1985) and Arthur (1989) by showing that transitions to most efficient standards may take place. They agreed that the historical precedents do cause fundamental differences in the subsequent development paths. However, they argued that the consequences of past decisions may be overcome and market's outcome can be improved by the choices taken in the present.

More recently, Verge (2013) provided a critical analysis of the literature on technological lock-in. On the basis on formal models, simulation and experimental literature, the author rules out path-dependence as the main drive in technological adoption. He argues that the methodology that has been used to capture this issue is weak and that other factors such as first-mover advantage, organizational inertia, hypersensitivity to initial conditions may explain markets' dynamics way better than the path-dependence theory.

Colla and Garcia (2004) present another challenge to Arthurs's path-dependence model. They propose a model of overlapping generations with forward-looking agents that form expectations about the future and act according to them in each period. They considered both cases of incompatible and compatible technologies, which exhibit network externalities. Their main finding is that an inefficient technology cannot become the market leader only due to its positive network effect, neither for compatible nor incompatible cases. Although, the authors observed path-dependence in agents' choices, they did not find any evidence of lock-in. Colla and Garcia (2004) concluded that lock-in in an inefficient state may occur only in the short-run and then a population eventually transfers to a more efficient equilibrium. Moreover, the researchers added that the probability of a technology adoption depends also on the availability of converters, which enable compatibility between two technologies. Converters speed up the expected time of adoption of a new technology and increase frequency of switching between two incompatible technologies.

The problem posed by the compatibility among technological standards has been an important issue from the very beginning of this literature. In a recent survey, Farrell and Klemperer (2007) stress the fact that incompatibility between standards slows down the speed of adoption of new technologies, limits freedom of individual choices and complicates population's switch from one equilibrium to another.

Network effect associated with an established consumers network generates switching costs, which are the costs of changing one technology to another technology. Users of new technologies are required to acquire some additional skills in order to use new products adequately. Moreover, switching for consumers would result in loss of the network effect associated with the previous technology. In this way, network effect constrains people to buy the same products over time, and the switching costs become a crucial factor of lock-in that binds consumers to suppliers of goods that were purchased earlier. Market with switching costs makes buyers depend on their earlier choices, because it is likely that this choice will define the vendor of the next purchases (Farrell and Klemperer, 2007).

Most often switching costs arise for purchases that require the follow-up service such as automobiles, software, and legal assistance (Larkin, 2004; Israel, 2005). Buyers find it costly or risky to switch from the original supplier to its competitor that produces substitute goods and, therefore lose all privileges from economies of scope. However, switching costs may be caused intentionally by firms that wish to maintain their consumers. Firms often apply price discrimination and other policies in order to distinguish their old customers that are locked-in on their production, new buyers and customers that are locked-in on the rival vendor (Shaffer and Zhang, 2000; Arbatskaya, 2001; Stole, 2007).

An instrument that can make a transition from one incompatible technology to another one easier is a converter, a device that supports compatible usage of the products of different technologies. Aggregating the number of consumers of each independent network to one common network, converters allow products or technologies of different standards to work together, thereby multiply the network effect (Katz and Shapiro, 1985). Converters allow a consumer to profit from the purchased product when no one else uses it through becoming a part of a consumers' network of the competitive good. Therefore, converters make consumers better off through reducing the risk of a transition to a new technology that doesn't have established consumers' network.

In a normal form game, an introduction of converters may be represented as a change of payoff matrix where a payoff dominant but risky strategy is substituted by a risk-dominant but not payoff-dominant strategy. While a payoff-dominant risky strategy represents a choice of incompatible technology, the presence of converters transforms it into a risk-dominant strategy that may give a lower payoff. In this case, miscoordinated actions of the players would yield positive payoff through compatibility of the chosen technology with its rival consumers' network. A lower final payoff of the risk-dominant technology may be considered a consequence of the expenditures on the purchase of a converter.

Witt (1997) presented a model where he derived conditions when a new technology in a market can be adopted, despite barriers created by network externalities and a threat of lock-in (1997). The author argued that the superior technologies displace inferior ones because they have a smaller critical mass. According to Witt (1997), an adoption of a technology with a lower critical mass is easier since a smaller fraction of initial adopters is needed to make all the followers benefit from the switch. Andreozzi (2004), however, suggested that critical mass depends not only on technology's efficiency but rather on its compatibility with previous standards. Therefore superior technologies do not necessarily have smaller critical masses, especially in the absence of perfect two-ways converters. Population resists less to innovations if they are compatible with the old standard. The author concluded that eventually a new relatively less efficient but compatible technology is more likely to be adopted than a new relatively more efficient but incompatible technology. Another view on the problem of transition was given by Choi (1996). His model of technology adoption showed that converters do not make a transition to a new incompatible technology less complicated and do not necessarily contribute to the creation of a new consumer network. While author agreed that incompatibility indeed might impede a switch to a new equilibrium in the presence of positive network externalities, he also argued that it induces new consumers to abandon the old technology if they expect it to soon become inferior in a market.

Young (1998, 2003) emphasized several factors of successful technology adoption, such as: the of extend of agents' interaction in small clusters, the network topology in general, and the advantage degree of the innovative technology. Later Young (2006) developed an agent-based model of a technology adoption with network externalities and implemented it for the local interaction network structure. His model is represented as Markov chain of very large dimensionality. The transition probability to each of its state depends on matching method, rules of strategy revision and agents' beliefs. Agents, which are boundedly rational, choose between two technologies, each of which generates positive network externalities. Agents best-respond according to information obtained from population sample but their choices are affected by random shocks. Therefore, there exists a large number of states where a transition from one to another convention is possible. According to Young (2006), a population will end up in an equilibrium characterized by a path of least resistance - the smallest number of mistakes needed to tip from one equilibrium to another. Such equilibrium is stochastically stable but inefficient. Young (2006) adopted a model of local interactions where agents may change their locations on a circle and showed that there may co-exist two equilibria in one population, although this situation is unstable. The author calculated the influence of the neighbor's choices on the choice of a player and concluded that the number of neighbors and their connections influence the long-run equilibrium selection.

Young and Kreindler (2014) studied topological properties of a diffusion of a new technology in a stochastic adoption process. In their model, the more neighbors of a player have adopted a new technology, the higher is the probability that he adopts it as well. In contrast to previous works (Young, 1998; Vega-Redondo, 2007; Jackson and Yariv 2007), where authors highlight the importance of a proportion of neighbors in the interaction structure, Young and Kreindler (2014) provide topology-free results (i.e. those that do not depend on the interaction structure). In line with existing literature on technology adoption (Griliches 1957, Bala and Goyal 1998), Young and Kreindler (2014) point out that the payoff gain is one of the main factors of technological adoption. They also refer to the amount of noise inherent to the model: the greater probability of mistakes promotes a faster innovation adoption. Applying to their model a global interaction with sampling, authors derive this inference irrespectively from size and structure of the network.

1.3.2 Experiments on Technology Adoption

Most experiments on technological adoption and transition are reduced to investigation of simple coordination games. Mostly, they investigate the possibility of lock-in and study equilibrium selection basing on the critical mass theory. Unfortunately, this method is hardly a realistic development of the adoption process. Coordination games allow to trace population's convergence to a particular equilibrium, however, they do not provide any clue of how occurs a technological transition from the old standard to a new one.

Keser et al. (2012) studied technology adoption with network externalities in coordination games. The authors discussed the relationship between risk-dominance, critical mass and the maximin criterion. Subjects that follow the maximin criterion should choose the maximal payoff in the worst case. In a technology adoption game, the worst outcome for a player is to be the only adopter of a technology. The payoff of such a player is given only by technology's stand-alone value – utility from using a technology independently, which does not include the network effect. Keser et al. (2012) noticed that the risk-dominant strategies have the largest stand-alone value – quite an intuitive result, though. Following the same logic, authors say that a technology with a lower critical mass, which requires less adopters to become profitable, is also represented by the maximin criterion. However, their experimental data did not show any explicit tendency of subjects to choose either a risk-dominant or a payoff-dominant strategy. Therefore, authors concluded that a technology is likely to be adopted when its relative payoff-dominance is high and riskiness is low.

Works that best reflect the nature of transition from one technology to another are the experiments by Hossain et al. (2009) and Hossain and Morgan (2010). Their experimental subjects were randomly assigned two types and had to choose between two competing technologies. Players benefited if they chose a platform with many opposite-type players, and were harmed by the presence of agents of their own type. In order to replicate the notion of standard technology, only one of two technologies was available in the first five periods. During the experiment, the monopoly power was consequently given to both the inferior and the superior technologies and to the cheaper and the more expensive one. The experiment has shown no effect of the past experience and expectations on a coordination on the inferior technology. Hossain and Morgan (2009) provided evidence that the lock-in phenomenon did not occur and that players were never locked-in on an inferior technology even when it enjoyed a monopoly power in the beginning of the game. Authors concluded that “the danger lies more in the minds of theorists than in the reality of marketplace” (Hossain and Morgan, 2009, p.11).

Several works have studied the influence of the network structure on equilibrium selection and particularly technological adoption. Jonard et al. (1998) found that the distance of interaction between two agents is positively correlated to lock-in event. As the size of the neighborhood enlarges, the probability of the lock-in on that particular technology increases. Delli Gatti and Gallegati (2001) through a computer simulation observed that the stochastic interaction among agents inside a network facilitates the convergence to the most efficient technology, which corresponds to the most efficient Nash equilibria.

Field experiments on the influence of the local interactions inside consumer networks gave positive results. Foster and Rosenzweig (1996) analyzed the impact of local interaction on the technology adoption and found that the farmers who were geographically close to the households that have adopted the innovation, adopted it faster than those who were not in that neighborhood. Conley and Udry (2010) studied social networks of farmers in Ghada. The authors distinguished informational and geographical neighbors and found evidence that the informational ones follow the choices of their neighbors if they happened to be successful.

1.4 Influence of Conventions on People’s Switching Behavior

Behavior in a society is usually shaped by people’s beliefs about what others consider appropriate, correct or desirable. Adherence to a particular convention that has been established in a society serves to its members as a social function that helps to distinguish the outsiders. Social conventions can even influence peoples' preferences unconsciously and affect the preferences that are usually considered private, such as political views or music tastes. The more public is a convention the more benefits it may provide for its members. A convention to drive on a right side on a road, for instance, is not just beneficial, but a life saving option.

Numerous studied aimed to investigate how rules or ideas persistent in a society influence individual attitudes to technological innovations. Any innovation begins as a deviation from an existing social convention. But given their strong persistence in a society, how may an innovation spread to the point to become a new convention? Most probably, a technological innovation would be successfully adopted if it is introduced right in the point when a society is already considering to abandon the outdated social convention in favor of a new one (Venkatesh and Davis, 2000). For instance, since smoking started to be considered as a pernicious habit both for a smoker and for the people around, a technological development offered an electronic cigarette - a solution that hit a market.

A convention is social phenomenon and it is rarely the case when a single individual may change it. An adoption of any technological innovation starts with its acceptance by innovators – resolute consumers that take the risk to abandon the old convention and shift to a new standard. Though they may be isolated from each other, people often follow their lead since it is an accessible way for members of the society to bond or signal solidarity. Adoption of a new technology is more likely to occur if the initial fraction of adopters has reached the critical mass – a share of population needed to make a shift to a new technology relatively more profitable for its subsequent adopters. The number of such deviators would depend on the strength of the convention that has been established in that society. Moreover, a transition from one convention to another, from one technology to a different one, will undoubtedly proceed faster if a new standard offers more advantages relatively to the old one.

1.4.1 Social Norms and Conventions

Social norms are customary rules that govern behavior in societies. They determine what is acceptable and what is not for particular groups or societies. Usually they arise unplanned and unexpectedly as a result of human interactions within small groups, develop and then spread beyond their boundaries. Norms represent a solution to social order and social coordination problems, which emerge in a society.

In its turn, a social convention is a regularity widely observed in a behavior of some groups of agents (Lewis, 1969). Social conventions are represented by promises or contracts that constitute an explicit agreement to follow particular rule. The research on social conventions has shown that their presence largely affects people's attitude to change. Conventions are present in every aspect of human's life and may remain unchanged over centuries. Familiar examples of social conventions are: speaking a particular language, using a currency, driving on the right hand side of the road, and so on.

Contrast to the definition of a social norm, social conventions do not have a proscriptive component. However, once a convention has been established, a deviator in such society might be considered as eccentric, strange or even be punished.

Nonetheless, the distinctions between norms and conventions have been blurred. The theorists that have been studying this issue acknowledge that eventually social conventions tend to turn into norms so that the difference between these two concepts may be in practice less sharp and short-lived. Therefore, these two aspects will be actually considered as synonyms further in the text.

David Hume first described a society as a collection of coordination games and proposed social conventions as solutions for recurring coordination problems (Hume, 1740). He noticed that once a convention has been established, it reproduces itself as the ordinary and "obvious" solution. More people are involved in a convention more it spreads in a society.

David Lewis (1969) analyzed conventions as Nash equilibria in coordination games with multiple equilibria. Further, such approach has been widely elaborated in the works of other researchers (Schelling, 1960; Ullmann-Margalit, 1977; Sugden, 1986; Young, 1993; and Bicchieri, 1993, 2006). The authors suggest that following a particular convention is a self-perpetuating solution to a coordination problem: since it has been established any unilateral deviation from it is costly. Adherence to such convention, as well as playing Nash equilibrium, is a "steady state" since each player acts optimally given the behavior of other players.

Lewis defined a convention as follows:

> A regularity *R* in the behavior of members of a population *P* when they are agents in a recurrent situation *S* is a *convention* if and only if it is true that, and it is common knowledge in *P* that, in any instance of *S* among members of *P*,
>
> 1) everyone conforms to *R*;
>
> 2) everyone expects everyone else to conform to *R*;
>
> 3) everyone prefers to conform to *R* on condition that the others do, since *R* is a coordination problem and uniform conformity to *R* is a

coordination equilibrium in *S*. (Lewis, 1969, p. 58).

Indeed, people randomly make decisions in isolation. The outcome of their choices depends on the actions and beliefs of other individuals that form the society. A convention, as well as Nash equilibrium, contributes to the mutual benefit of players who execute it. In the same time, it does not need to result from explicit promise or agreement. It is of one's own immediate interest to follow the convention, which is, for instance, to speak a particular language that everybody around is speaking; otherwise that person will not be able to communicate and reach the goal of coordinating with other people. A choice to follow a convention is conditional upon expecting most other players to follow it. Given the belief that each player expects all the others to obey the convention, each player has a reason to obey it himself. Adhering an established convention, people expect each other to respect the existing behavioral rule and this tendency constitutes the hierarchy of people's expectations. The rationality of players' choices, in this context, is contingent on the actions and expectations of the others.

Conventions may arise as an intuitive coordination mechanism and serve as a successful coordination device in the absence of communication. In more recent times, Schelling (1960) suggested that, among a variety of available options, people who aim to solve a coordination problem tend to choose an option that is more prominent than others or seems a priori more reasonable. Schelling (1960) called such option a *focal point* – an alternative that somehow draws the attention of the decision-maker. Without applying any sophisticated piece of reasoning, individuals may coordinate efficiently by choosing a solution on intuitive basis. Schelling provided real-world examples of salient options referring to them as to "cultural conventional priority". For example, if two individuals need to coordinate in choosing a positive integer they are most likely to choose “1”, although any other number would be a priori equally good. Similarly, if two individuals must co-ordinate in choosing Head or Tail they will be more likely to choose Head. To strangers needing to meet somewhere in New York City are most likely to go to Central Railway Station at noon.

Salience of the options in the examples above may be characterized by their uniqueness or precedence. Lewis (1969) expanded the concept of precedence and the role of past experience in the establishing a social convention and suggested that the repetition of the actions that succeeded in the past leads to the emergence of a corresponding convention, which eventually turns into a norm. Since a lot of conventions have originated from historical precedents, they have a deeply installed foundation, which causes their strong persistence in society.

Convention appears as commonly known mutual best-response that persists because of individuals’ beliefs that their partners will also best-respond. Since conventions correspond to strict Nash equilibria in coordination games, unless a considerable number of participants have a reason to deviate from the existing convention, players should stay at their previous practice and coordinate on the old equilibrium (Lewis, 1969; Sugden, 1986).

The idea that conventions can only work if they are common knowledge has been put in question by evolutionary economists like Binmore (1994) and Skyrms (2004). Binmore (1994) agrees that social norms must correspond to Nash equilibria of a game. If players have an incentive to switch to a more profitable strategy a social norm would not survive as a convention. However, Binmore rejects the idea that conventions must be commonly known best-responses in order to sustain coordination in a population. The evolutionary approach explains the emergence of coordination on the basis of simple learning procedures and hence denies the idea that conventions need to be common knowledge.

Skyrms (1996, 2004) claimed that evolutionary games do away with the idea that coordination problems are solved by means of “focal points”. He argued that the least successful strategies are less represented within a population and are replaced by more successful ones. This process explains the emergence of social conventions without any appeal to the concept of salience. Bicchieri (2005) proposed that a convention is rather a justification than a reason to conform particular coordination equilibrium. She suggested that under the assumption of rationality common knowledge of convention is unnecessarily. On the example of corruption, as a socially inferior phenomenon, she pointed out that inefficiency is only a necessary but not a sufficient condition for a convention to demise.

A plausible explanation to the question why conventions may persist for a long time was provided in theoretical papers by Sokoloff and Engerman (2000) and Acemoglu (2003). They explained it from the political point of view, as an interest of a ruling elite in maintaining its status quo in order to retain its power. Examples of these cases can be represented as slavery, monopoly power, and political dictatorship. A transition to a new, more effective form of power can be achieved through revolutions. The success of a revolution largely depends on people’s ability to make simultaneous decisions and to coordinate in breaking the old rules. If a revolution succeeds and society proceeds to a new equilibrium path everybody would be better off. Otherwise, in a case of a failure, the revolutionists are punished and that leads to a stronger deadlock in an inefficient state.

A game-theoretic framework aims to analyze this problem by involving repeated interactions. In repeated encounters, individuals have an opportunity to learn from each other's behavior and evaluate the outcomes of their decisions. According to the evolutionary approach, behavior is adaptive. Therefore, a population replaces a strategy that fared poorly in the past with a strategy that performed well. Indeed, real-life evidence suggests that a behavior that have been considered conventional for ages may finally die out, for instance smoking in public or discriminatory rights for minorities.

Since following a particular convention constituted in a society benefits one's interests, participants' common beliefs and expectations to uphold the agreement hamper any attempt to shift to a new practice. A transition between two conventions that differ in efficiency may be represented as a transition between equilibria in a game with multiple equilibria. Take the stag-hunting paradigm – a typical example of a coordination game with two Pareto-ranked equilibria. There are two equilibria: to hunt a stag and to hunt a rabbit, which demonstrate a conflict between risk and efficiency. Hunting a rabbit may spread as a convention that everyone conforms to due to players' uncertainty about the other's actions. In alternative, hunting stag gives a higher payoff for everyone, but only if other participants also hunt the stag. A possible argument could be that a person who hunts rabbits does not prefer that the other player do likewise. However, hunting alone or in small groups is not profitable and there exists a successful deviation, which requires a large share of population to adopt new behavioral rules and to follow a new convention. Moreover, a connection between a single player payoff and others actions is tighter if the stag hunt game is played in evolutionary context – in a large population of players where each player is interacting with the population as a whole. Such design adds to the game a network effect, so that the payoff for hunting a rabbit also depends on the critical mass of adopters of the same strategy: the higher is the number of adopters of any strategy in a game – the higher is the payoff for its each subsequent adopter.

A stag hunt game illustrates a real-life dilemma of selection from numerous candidate conventions, which differ in their characteristics and their efficiency depending on the total number of adopters. Considering “hunters” as a potential bunch of voters for a new act of civil rights or consumers of a new version of a technological product, the potential success of their actions depends on the number of equivalent actions taken by other members of their population. With the increase of the number of initial adopters, the expectations of others concerning a success of the innovation grow and, consequently, a probability of a transition to it. The higher is the number of voters for a new law – the higher is the probability that is accepted and therefore the higher would be the benefit of its supporters; similarly with the increase of the number of adopters of a new social network, its adopters may stay connected with more people, which is actually its main goal. Therefore, an increase of the threshold of initial users of an innovation increases the payoff of its adopters and consequently its establishment as a new convention.

Research by Belloc and Bowles (2013) attempted to explain the persistence of inferior conventions and mechanisms that induce transitions to a more efficient state. They study evolutionary dynamics of a mutual best-response in an economy of two classes (employer and employee) as a cultural-institutional convention. Their model has two Pareto-ranked Nash equilibria and these two states are represented by Markov process. In their experiment agents of both classes had to adopt one of the proposed contracts. Both classes consequently update their contract in order to maximize their expected payoffs. The agents in the model are boundedly rational, and with certain probability make mistakes and deviate from the best-response. The main peculiarity of the model is that the authors introduced the measure of agent's rationality: the larger it is the smaller is the probability that the agent deviates from the conventional strategy, which is the best response. A transition from one convention to another, even if the later is Pareto superior, is less probabilistic the higher is agents' degree of rationality. For an adoption of an alternative convention it is necessarily that at least one of the players makes a mistake and chooses it while all others are choosing another convention. When this process is started, consequent best-responding agents enter the basin of attraction of a new convention by best responding to a "mistake". Thus, authors showed that the speed of transition depends on the degree of rationality of the population and the time required for it is increasing in it. Authors conclude, that even in the cases when alternative conventions are largely Pareto-superior, a switch may not happen if agents are sufficiently rational and don't make mistakes. Moreover, authors mention the costs of deviating from a status-quo convention to a new one is analogous to the switching costs. Belloc and Bowles (2013) provide an example of autarchy as an inferior convention and a free trade as a superior one. A possible switch from autarchy will cause the costs of deviating, which delays convergence to a superior convention. Furthermore, authors traced a dependency of an expecting waiting time of a switch from a group size. Thereby, a transition from one convention to another proceeds faster and easily in small populations. It also matters which kind of society is subject to changes. If a transition is happening in an "individualist" society (the one where agents' action do not affect each other) it takes more time than a in a collectivist society where one person's deviation will induce other members of the group to deviate as well. Individualistic society might be represented by a global matching protocol, while a collectivist society corresponds to a high clustering interaction structure in experimental approach.

1.4.2 Technological conventions

Social conventions and norms that persist in a society are important factors that affect the potential success of innovation in this particular society. Norms and expectations in a society define which technology is more likely to arise and diffuse into practice. These norms of behavior could give an initial idea of which technological innovations are most likely to be accepted. For example, a wide spread of social networks popularity caused a development of smartphones with wi-fi and all the corresponding options to access these networks. Moreover, social conventions may be considered as priorities for the choice of financing a particular innovative project. Research in technology acceptance considers social norms as an important indicator of consumers' new technology adoption behavior (Venkatesh and Davis, 2000). Therefore, a concept that a social innovation provides is likely to dictate the proprieties for the development of a new technological innovation.

Nonetheless, social and technological innovations do have several common features. Both of them are social phenomena and both of them require certain fractions of initial followers to be successfully adopted. Since deviator from an established convention may face social sanctions in one case and a loss of network benefits in another, it takes much time and effort for a transition from one convention to another. However, each subsequent adopter of a new convention reduces the uncertainty of other market participants about its risks and benefits. Even a minority position is able to eventually become a convention.

A difference between social and technological conventions is in the nature of their emergence in a society. Social innovations most commonly arise arbitrary, as a result of people interactions. In contrast, technological innovations take a long conscious path before appearing in a market: from a development of an idea, to the projection of a hardware (software) and its financing.

Moreover, a term "social innovation" does not have a single commonly agreed definition. It is used to describe a very broad range of activities: from models of social development to a new system of rights. Considering social innovation in its normative definition as a prescription about what's considered normal or ought to be normal, different social conventions would present different ideas about the social development path. Therefore, it is hard to name two different social conventions that easily co-exist in the same society. In the same time, a lot of technological innovations are compatible between each other and provide benefits from their mutual usage to its consumers.

Adhering to a convention that existed for a long time, facilitate people's coordination and may reduce risk. Although following a convention is a strong method to solve coordination problems, this practice may lead to inefficiency. Using the same standards for a long time period may eventually become inefficient and inconvenient. Particularly powerful technological conventions were observed to delay technological development and slow down economic advancement keeping the population in inefficient state (David, 1985; Rip and Kemp, 1998; Unruh, 2000).

There are many examples of a market failure caused by the adherence to inefficient conventions but the most popular one is the QWERTY keyboard (David, 1985). In David's familiar story, there are two competing technologies: a status-quo old standard QWERTY keyboard and a newly developed Dvorak keyboard. The

QWERTY keyboard layout originated in the nineteenth century, when it was developed for typewriters. Its main propose was to minimize the speed of typing by means of placing commonly used letter-pairs far away from each other in order to avoid jams of type bars. By contrast, the Dvorak keyboard layout was designed to increase typing speed, reduce finger fatigue and the number of errors by balancing the working load between hands. David claimed that numerous tests have shown that the Dvorak keyboard is vastly superior to the QWERTY it is easier to learn. However, the Dvorak keyboard has never been adopted by the general public. People found it too costly to relearn to type on a keyboard of a new standard, and apparently, since there were too few Dvorak users, enterprises did not produce typewriters with Dvorak keyboard. Thus, in this case where the new standard was giving obvious benefits, which exceed switching costs, the transaction did not occur. David used the failure of Dvorak's keyboard to show the importance of history in determining individuals' choices and the threat from persistence of inefficient conventions. His conclusion is that people might be unwilling to break an established convention even if the adoption of a new standard would bring about a Pareto improvement.

Another familiar example of coordination failure is the battle that started in the late 70s between two incompatible formats for video recording: Beta and VHS. There are still disputes about the advantages of each standard which lead to a conclusion that the main factor of decision-making between two technologies were not their properties but rather the consumers' preferences. Sony Management that produced videocassettes believed that consumers would appreciate the transportability of the cassette more than accessible recording time. Hence, Sony released the cassettes based on Beta standard and become market leader for the next two years. However, with the appearance of VHS cassettes produced by Matsushita in a market consumers switched to the new standard. Larger tape format of VHS managed to outperform Beta and later dominated the market thanks to its lower price and longer play time, which consumers found more useful. After an empirical analysis of the U.S. media market between 1978-1986 Ohashi (2003) pointed out that the Beta standard would have remained a dominant standard if VHS hadn't chosen an aggressive break-through politics of market entrance on an early stage of competition.

These studies have met a lot of criticism as examples are easy to find in which superior technological standards eventually replace the old conventions (see Liebowitz and Margolis, 1990, 1994; Vergne, 2013). Kay (2013) presented series of tests that rejected the notion of QWERTY as an inferior convention that has prevailed just because of historical accident. Instead, the author defined QWERTY as a well-designed efficient innovation of that time. He argued that the QWERTY dominance should be considered as the result of market's increasing returns rather than a path-dependent phenomenon, and hence suggested to analyze these two aspects separately.

1.4.3 Experimental Investigation of Conventions

Experiments that are designed to study the emergence of conventions and their influence on behavior of individuals are often obstructed with difficulty to re-create these events in a laboratory. Establishing a convention requires common history of a play and much time – conditions that are difficult to obtain in a controlled laboratory environment. Apparently, this is the reason why conventions have been studied mostly theoretically and did not become a popular subject for experimental testing.

Thus, experimental evidence on the nature of convergence is mostly provided by the analysis of people's tendency to sustain salient equilibrium in coordination games.

The early experimental evidence was in favor of the theory that conventions spontaneously emerge that help people to solve coordination problems. Van Huyck et al. (1997) investigated experimentally agents' ability to adopt a conventional way of play in coordination games. Authors considered two games - with and without labeled strategies - and observed an interesting result. In the game with no labels, players failed to coordinate and played the mixed strategy equilibrium through the game rounds. While in the game with labeled strategies, an efficient pure strategy equilibrium emerged rapidly since labels facilitated understanding the convention rules to the players. Authors also highlighted the importance of the matching protocol for equilibrium selection in coordination games. Crawford et al. (2008) obtained the analogous results in their experiment on symmetric pure coordination games. They found that labeling salience served as an effective coordination device only in symmetric games, where it does not conflict with the established convention.

Guala and Mittone (2010) conducted an experiment, which goal was to check whether the social conventions have a tendency to turn into norms. Their participants played a 3-people coordination game where they had to coordinate on one of the two equilibria in a game. Later, one of the players was given an incentive to switch from a usual pattern to a non-conventional strategy, which yielded him a relatively higher payoff and a zero payoffs to other two players. In this way, the game turned into a kind of a dictator game. The experiment has shown that the cooperative repetition of the collective task leaded to a strengthening of the convention power. The experiment revealed that the potential deviator perceives other players' actions as a demonstration of reciprocity and if the convention is strong enough will uphold following it despite his individual incentives. Interestingly, the experiment has shown that younger people were more likely to change their strategy.

Not much research has been done in experimental investigation of maintenance of inferior conventions. Theory explains its persistence as the only mutual best-response known to all of the participants of a market. With time, an existing convention becomes a salient coordination device and individuals would choose it despite its possible inefficiency. The results of the “pie game” experiment by Crawford et al. (2008) support this idea. Its participants were randomly matched in pairs. They had to choose between three alternative strategies, one of which had a reduced salient payoff equal for both players and two other strategies gave higher payoff to first and to second player respectively. The experiment showed that players tended to choose the salient low-payoff label and ignore more efficient options. In the setting with more alternatives, players became even more risk – averse and coordinated on a salient, low-payoff strategy in fear of the low payoffs determined by miscoordination.

1.5 Conclusions

Large streams of literature provide theoretical and experimental insights on equilibrium selection, technology adoption and the emergence of conventions. A lot of work has been done in order to understand which outcome will be selected in the long-run. Game theoretical models based on the notion of stochastic stability lend support to the idea that the most likely outcome is coordination failure on the inefficient, risk-dominant equilibrium. However, a significant number of experiments disprove this theory and provide evidence of populations' convergence to efficient equilibrium. Researchers agree that a lot of factors influence the result of equilibrium selection, among them the size of the interacting groups, availability of feedback, number of repetitions and so on. Both experimental and theoretical works have shown that network architecture with high clustering and availability of feedback favor convergence to the efficient outcome.

Many questions concerning the way conventions emerge and remain stable remain to be explored. Not much experimental research has been done settings in which subject must react to the introduction of a novelty. Most experiments were designed to study the way an equilibrium is selected in a coordination games. Much less has been done to explore the way a population may switch from one equilibrium to another. This is relevant for real world situations, where innovations rarely appear simultaneously. Most of the choices people face are between a new option and an established convention that has been working as a focal point and a mutual best-response earlier. The chapters that follow aim to fill this gap.

2. Adoption of a New Technology: Efficiency vs. Compatibility

2.1 Introduction

This work studies the process of a new technology adoption in a laboratory environment. Much research in this field has been done through implementing an empirical analysis of technology adoption and diffusion (Cooper and Zmud, 1990; Evans et. al 2006, Venkatesh et al. 2003; Rauniar et al. 2014). Yet, such approach omits important microeconomic and behavioral factors that may affect people's perception of innovations, such as risk-aversion or adherence to the conventional technology. Studies that attempted to analyze technology adoption experimentally mostly performed simple coordination games, which design hardly reproduces the nature of the adoption process. There is clearly a difference between solving a co-ordinaton game and adopting a new technology or a new convention. In the first case, the two (or more) alternatives are presented at the beginning and are on an equal footing. In the second, there is already an existing technological standard (or a social convention) and a new (perhaps more efficient) alternative emerges.

The present study aims to reproduce conditions that best correspond to the natural process of technology adoption. Hence we concentrate on the more realistic setting in which a new technology appears in a market which is already monopolized by another technology. My study analyzes which particular characteristics a newly introduced technology needs to have in order to break the old habit and to be adopted. Unlike other experiments that artificially created initial power for the old technology (Hossain et al., 2009; Hossain and Morgan, 2010; Heggedal and Helland, 2014), my work involves voluntary establishment of a convention by players before they face an adoption task. Such modification adjusts a coordination game into an adoption task and provides a more plausible experimental representation of the process of technological adoption.

The experiment includes ten pre-play rounds of a simple coordination game where players are free to choose an option from a pre-determined set of possible technologies. We expect these rounds to be sufficient to observe the emergence of a technological standard. A new strategy, corresponding to the new technology, is introduced into the game only after these pre-play rounds. This experimental design illustrates two important points. First, the way the equilibrium is selected in the pre-play rounds is likely to influence the probability of transition to a superior standard. One may expect, for example, that the harder it was to coordinate in the pre-play rounds, the more difficult it would be to switch to a new strategy, even if efficient. Second the presence of a conventional strategy might be an important factor in players' attitude to technological transitions. When the existing standard has been chosen in the early rounds of the game, subjects may be less willing to change their strategy

From a theoretical point of view, the experiment relies on the stochastic approach to equilibrium selection pioneered by KMR (1993), Young (1993) and Ellison (1993). As anticipated in Chapter 1, the main conclusion of all these models is that a population playing a 2x2 coordination game will spend most of the time at the risk-dominant equilibrium, even when not Pareto efficient. This conclusion is based on the observation that the size of the basin of attraction of the risk-dominant equilibrium is larger than the payoff-dominant. In the presence of mutations, a transition out of the risk-dominant equilibrium is thus more difficult than the opposite transition.

My experiment evaluates the validity of these predictions with two basic innovations with respect to the existing literature. First, I will explore *transitions* from one equilibrium to another to check whether it is true that it is always more difficult to escape the risk-dominant equilibrium. Second, I will provide an environment in which subject face the type of noise that is required by this class of models, which will allow me to test the propositions concerning the ease of transition in the limited time span of an experiment.

Another important feature that affects coordination rate and influence equilibrium selection is the matching algorithm. Theoretical models described above predict that the risk-dominant equilibrium is the unique long-run equilibrium independently of the matching protocols, although local interaction speeds-up the convergence to the long-run distribution (KMR, 1993; Ellison, 1993). However, the existing experimental evidence showed that the matching mechanism and interaction structure influence which equilibrium is selected. The existing literature shows that while when agents interact in a circle the most common outcome is the risk-dominant equilibrium, in local interaction with high-clustered networks the observed equilibrium is the Pareto-efficient one (Berminghaus et al., 1998, 2002; Cassar 2007; Kirchkamp and Nagel, 2007). We address this issue by running experiments under different matching rules. In order to determine which interaction structure is more effective for successful technology adoption, all treatments are conducted under random matching and local matching protocols.

2.2 Related Literature

Experimental investigation of a technology adoption process in a competitive environment is quiet scarce. Similarly, until recently very few experimental works focused on the analysis of network interactions. In the present section I give a critical review to the experiments that are most closely related to my research topic. Namely, I will overview the works by Hossain et al., (2009), Hossain and Morgan (2010), Heggedal and Helland (2014) on platform adoption in the presence of network effects; and works by Cassar (2007) and Corbae and Duffy (2008) that consider coordination games in different kind of networks.

2.2.1 Market tipping experiments

Hossain and Morgan (2009) investigated the QWERTY phenomenon, described by David (1985). The researchers first studied the possibility of technological lock-in experimentally. They performed a platform adoption experiment in a two-sided market, which included both network effect and market impact effect. The authors used a model by Ellison and Fudenberg (2003), which demonstrates the existence of a multiple possible market-split equilibria in a market of two competing platforms. The participants were divided into two types and assigned into groups of four players. They had to choose between two competing platforms, which differed in access fees and efficiency. One's payoff from choosing each platform depended negatively on the number of adopters of his same type and positively on number of adopters of different type. In order to recreate the notion of a standard platform, only one of the two options was available in the first periods of the game. Depending on the treatment, the standard platform was modeled to be inferior or superior, cheaper or more expensive than the new one. The results of the experiment provided a clear evidence of tipping to a superior platform in any of these treatments, especially when the inferior platform was given initial power. A slight evidence of a novelty effect was detected, though it was insignificant. The authors observed that the market always tipped to the platform that was both efficient and risk-dominant. In the case when the efficient platform was associated with risk, the market still converged to it but it required more time and experience from the players. Therefore, Hossain and Morgan (2009) concluded that the QWERTY effect and lock-ins into an inferior platform are improbable and that “the danger lies more in the minds of theorists than in the reality of the marketplace” (Hossain and Morgan, 2009, p. 440).

A subsequent work by Hossain, Minor and Morgan (2011) continued their previous research but concentrated on the market structure. They studied tipping in technology adoption games with differentiated platforms. The showed that for homogeneous platforms – equally efficient in matching players – the market tipped to the platform with the lowest access fee. In a case of differentiated platforms, the market also tipped to the cheapest platform, which was both Pareto and risk-dominant in that treatment. The market also tipped to the Pareto-dominant platform when it was more expensive, although this required more time. The market converged to the outcome in which the two technologies coexist only in the treatments where risk-dominance predicts tipping to the cheapest platform and Pareto dominance to the most expensive. However, the researchers note that the Pareto-dominance is a better predictor for experienced players.

Heggedal and Helland (2014) replicated the experiment by Hossain and Morgan (2009). To test its remarkable result concerning efficiency, they introduced inflated out-of equilibrium payoffs to the adoption game. They conducted two kinds of treatments. In the first, the inflation did not affect the risk-dominance of the superior platform. In the second, the superior platform became risk-dominated. Since in the second case there was a conflict between risk-dominance and payoff-dominance, such inflation may have lead to a coordination failure for the second case but not for the first. Despite the game-theoretical predictions that out-of-equilibrium payoffs should not impact the pure strategy equilibria or security levels, the outcome of both games changed dramatically. In all treatments, markets no longer coordinated on the superior platform, choices of which fell to 40%. Moreover, the authors found a strong evidence of the fist-mover effect. Particularly, when an inferior platform enjoyed initial power, further coordination on a payoff-dominant platform was significantly hampered. Based on these results, the authors argued that path-dependence impacts significantly market efficiency. Their conclusion is that Pareto-dominance cannot be considered as a reliable mechanism for predicting the outcome of a coordination game and proposed that players are rather guided by initial level-k reasoning and subsequent payoff reinforcement learning.

The experimental research above is rather controversial. While Hossain and Morgan (2009) and Hossain, Minor and Morgan (2011) present experimental support for the Pareto-dominant result, the work by Heggedal and Helland (2014) completely disproves their arguments providing a clear evidence in favor of technological lock-in and path-dependency. Nonetheless, such ambiguity is quite common for experimental investigation of coordination games. Although a conflict between risk-dominance and Pareto-dominance itself constitutes a large stream in experimental literature, this problem was not given enough space in the works above. The authors mentioned risk-dominance and Pareto-dominance as possible selection criteria but their research is rather focused on market tipping in general. Given the design of their experiment, which includes network effect in matching markets, it is difficult to capture the influence of each of these criteria on the final result.

A common component of the market tipping experiments by Hossain and Morgan (2009), Hossain, Minor and Morgan (2011), and Heggedal and Helland

(2014) that can be considered to be weak is the way of assignment of the initial monopolistic power. Seeking to create a monopolistic power, the researchers made one of two platforms unavailable for several play rounds. However, such artificial method eliminates the need to coordinate and, consequently, the effort needed to achieve this coordination. In this way, it is likely that the players do not perceive the initial power of the incumbent platform, and hence it does not affect their further behavior. In the current study I will present the experiment, which provides a more natural way to establish a standard platform.

2.2.2 Experiments on interaction structure in coordination games

Recently a lot of attention has been given to the experiments that research how the network structure and matching procedures affect coordination in the lab. Mostly, these studies agree that a Pareto-efficient outcome is achieved in some interaction structure.

Cassar (2007) performed a laboratory experiment on coordination and cooperation in games with both Pareto-dominant and risk-dominant equilibria. The author analyzed equilibrium selection in local, random and small-world networks. In the random network treatment, relations between individuals were built randomly with equal probability. In the local network treatment, the players were arranged in a circle and interacted only with their most immediate neighbors. The small-world structure had properties of both structures above: players were first arranged around a circle and interacted with the closest members. Then, few links were created between players on the opposite sides of the circle. The game participants had access to the payoff matrix, a short running history of their own and their neighbors past actions and payoffs during the play. The experimental results showed that in all three treatments the majority of players converged to the payoff-dominant equilibrium, although with faster convergence in the small-world network. Moreover, in the small-world network the overall level of coordination on the payoff-dominant equilibrium was 7.5% higher than in the local network and 29.5 % higher than in the random network. Cassar (2007) explained such high coordination on the efficient equilibrium in the small-world network by its architecture structure. The author concluded that the extent to which agents are connected to each other and a short average distance between players, inherent in the small-world network, increase the probability of efficient coordination.

However, Cassar's (2007) remarkable results concerning convergence to the Pareto-efficient equilibrium in all of the network structures are easily explained by path-dependence process. The initial conditions in all of the treatments (except one) of the experiment corresponded to the basin of attraction of the payoff-dominant equilibrium. Therefore, since the experiment did not include any perturbation, a dynamic process led the population straight towards the payoff-dominant equilibria. The mass of the adopters needed to make the payoff-dominant strategy more profitable than the risk-dominant one was already accumulated at the beginning of the play, which made the efficient strategy a best-respond. Without the transitions between different best-respond regions, a payoff-dominance it cannot be considered a paramount factor of equilibrium selection but just a result of a path-dependence process.

Corbae and Duffy (2008) also tested equilibrium selection in different kind of networks. In their experiment, the authors divided the participants in groups of four players that formed three different interaction structures: global, local and "marriage" (where players form two independent pairs each connected with one link). For the first ten periods, the subjects played a coordination game in which the Nash equilibrium was both Pareto efficient and risk-dominant. After a few rounds, the play converged to that equilibrium in all of the networks. Next, the payoff matrix of the game was changed in a way that the selected Nash equilibrium remained Pareto-efficient but no longer preserved its risk-dominance The authors aimed to explore if the players would keep coordinating on the efficient equilibrium if no subject was forced to choose another strategy. As a result, the experiment has shown that in all of the networks the players remained playing the established equilibrium strategy even if it has become risky. The second treatment of the Corbae and Duffy (2008) experiment included the introduction of a "mutant" player after the modification of the game. The "mutant" player was a randomly selected player in each network who continuously received endogenous shocks that forced him to play a non best-response strategy. In fact, that player could not make another decision – the computer was choosing the risk-dominant action for him in every round. All other players in the group were aware of the presence of such a player but did not know who he was and his position in the network. Contrary to the results of the first treatment, in the treatments with a shocked player the equilibrium selection depended on the network structure. The experiment showed that the global interaction structure was resistant to shocks and players still played the Pareto-efficient strategy, while the local and the "marriage" structures failed to retain it and soon converged to the risk-dominant equilibrium. Authors explain it easily: in the local and "marriage" networks it is easy to understand who is the shocked partner and to play the best-response to his strategy. Contagiously, this best-response, which is playing the risk-dominant strategy, spreads to the rest of the network.

This experiment challenges the robustness of the established equilibrium in different interaction networks. However, the authors presented the transition from the established Pareto-efficient equilibrium to the risk-dominant one, but not *vice-versa*. Therefore, the experiment says nothing about how the players would choose when they are first conditioned on a Pareto-dominant equilibrium (which is also risk-dominant), which is then mutated into an inefficient (but still risk-dominant) equilibrium. Moreover, Corbae and Duffy (2008) introduce noise in the model in a rather crude way. In their experiment, noise modeled as an exogenous variable modeled as an external computerized intervention.

The experiment provided in the current work has common features with all of the studies described above. Considering all advantages and disadvantages of the previous studies, it seeks to explain equilibrium selection in coordination games in local and global networks. I concentrate on investigating population's transitions associated with breaking the old equilibrium – risk-dominant or payoff-dominant – as a method to test the predictions of the theoretical models. Also, I found a way to introduce noise in the experiment that is more natural than the way the same result is obtained in Corbae and Duffy (2008).

2.3 Matching procedures

One of the methods discussed in experimental literature that affects equilibrium selection in coordination games is the matching structure (see van Huyck et al., 1990; Berninghaus and Schwalbe, 1996; Berninghaus et al., 1997, 2002). There are many ways of organizing subjects in a network and implementing their interactions but the most common are the global matching protocol and the local matching protocol. In the present section I will discuss the main differences between the models of global and local matching, which were used in the current experiment, and analyze the mechanisms by which they may lead to different outcomes.

2.3.1 Global matching

The global matching procedure usually requires a large population of subjects that are randomly matched. At each round subjects are randomly picked from the whole population and matched in pairs so that any pair of subjects has equal probability of being connected. Since each agent faces a new partner every round, this type of matching makes practically impossible players' influence on other's choices and minimizes the occurrence of repeated games effect.

In my experiment I adopted a slightly different technique for global matching, which is a closer approximation to the KMR model (1993). I assume that each agent interacts with the population as a whole. According to it, each player is dependent not only upon his partner's choice but on the general decision outcome of the whole population as an average product of their individual choices. In this way, an average per capita payoff of a strategy that prevails in a population gives a higher compared to the average per capita payoff of strategy that is executed just by a couple of individuals.

Consider *N* agents who repeatedly play the 3x3 symmetric coordination game below, where a>c and d>b so *(A,A), (B,B), (C,C)* are all Nash equilibria. Strategies *A* and *B* are equivalent. When restricted to these two strategies this is a pure coordination game giving a zero payoff in case of miscoordination. We assume that d>a, so that the (*C,C*) equilibrium Pareto dominates (*A*,*A*) and (*B*,*B*) and that (a−c) > (d−b) so that equilibria *(A,A)* and *(B,B)* are both ½-dominant[3].

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[3] The concept of half-dominance was first mentioned by Harsanyi and Selten (1988) as an instrument to measure the riskiness of an equilibrium and further discussed Morris et al. (1995). In a 2x2 game, a strategy is said to be half- dominant (or risk dominant) if it is the best response when the other player is equally likely to pick any of his strategies. Morris et al. (1995) developed further this concept and provided a formal definition of "p-dominance" for generic symmetric games with *n* strategies. A strategy is p-dominant if it is a best reply to any mixed strategy that puts at least probability *p* on that strategy. This definition contrast with Harsanyi and Selten's (1988) concept of ½ dominance for the

	A	B	C
A	a, a	0, 0	b, c
B	0, 0	a, a	b, c
C	c, b	c, b	d, d

Table 2. 3x3 Coordination game

The decisions are assumed to be taken in discrete time, $t=1,2,\ldots$ In the beginning of each period t, a player i chooses his strategy s_i from the set of possible strategies $s_i \in \{A, B, C\} = S$. Let $NA \in \{0, 1, \ldots N\}$ be the number of subjects adopting strategy A at time t, $NB \in \{0, 1, \ldots N\}$ be the number of players adopting strategy B at time t, and $NC \in \{0, 1, \ldots N\}$ be the number of players adopted the strategy C at time t. Then the average payoff of a player who chose strategy A, B or C respectively will be:

$$\Pi_i(A) = \frac{(NA-1)*a+(NB)*0+(NC)*b}{N-1};$$

$$\Pi_i(B) = \frac{(NA)*0+(NB-1)*a+(NC)*b}{N-1};$$

$$\Pi_i(C) = \frac{(NA)*c+(NB)*c+(NC-1)*d}{N-1};$$

KMR (1993) argued that in the games with multiple equilibria the fundamental factor of final convergence is the number of mutations required to move from one equilibrium to another. When restricted to 2X2 games (as it would be the case if attention is restricted to strategy A and C, for example) to escape from the basin of attraction of a risk-dominant equilibrium requires more mutants (players that do not

nxn coordination games that involves pairwise comparison between all strict Nash equilibria in the game, p-dominance concept is associated with a comparison of all strict Nash equilibria. In evolutionary games the notion of p-dominance is relevant because when p<½, a strategy is a best reply when it is played by *less* than half of the population. This implies that to escape the basin of attraction of that strategy requires more than half of the population to mutate.

play a best-respond strategy) than to escape from the payoff-dominant one, and therefore is more difficult. Since a risk-dominant equilibrium has a larger basin of attraction, the probability that a population starts in it is higher than the probability that the players start in a payoff-dominant equilibrium with a smaller basin of attraction. In games with more than two equilibria the computation of basins of attraction is more complex, as the examples in Section 2.5 show.

2.3.2 Local Matching

Ellison (1993) was the first to adapt the KMR model to a setting with local interaction. In contrast to the random matching rule used by KMR, Ellison considered the case when players interact only with a small subset of other players rather than with the whole population. Local matching protocol allows to model a setting in which a person's social circle is limited by members of one's family, friends and colleague, although the social neighborhoods of different of people may overlap.

Ellison (1993) considered an example when N individuals are allocated around a circle so that each individual i interacts with 2 immediate neighbors: one on the right and one on the left (Figure 1). So, the matching rule is:

$$\Pi_{ij} = \begin{cases} \tfrac{1}{2} \text{ if } i\text{-}j \equiv \pm 1, \\ 0 \text{ otherwise.} \end{cases}$$

Each period a player revises his decision about which strategy to choose taking into consideration the distribution of the choices of his neighbors in the previous periods. Players play a myopic best-response to the previous state of the population and with a small probability they make a mistake.

To see how the model works, consider first a case in which the population is at the equilibrium that is not risk-dominant. Because the neighborhood of each player is made by only two other players it takes only one agent that plays the risk-dominant strategy, for it to be the unique best-response for all his neighbors. Because of this, the neighbors of the only mutant will switch to the risk-dominant strategy and so will do the neighbors' neighbors and so on. So the risk-dominant strategy spreads contagiously to the whole network from a very small number of initial adopters. In the opposite situation, where all the network of agents plays a risk-dominant strategy, one mutant that switches to the payoff-dominant strategy is unable to start a reverse process. The neighbors of the mutant will keep playing the risk-dominant strategy, which remains a best-response. In this way, Ellison's model predicted that under best-reply learning, the risk-dominant strategy is the unique long-run equilibrium in the local matching circular city model. Ellison's (1993) findings concerning the local interaction protocol fully support KMR's theory with the only difference that convergence to the stochastically stable distribution is faster as one transition only requires one mutant to happen.

2.4 Hypotheses

In stochastic evolutionary models the long-run distribution depends on how easy is to move from one equilibrium to another in terms of mutations. In my experiment I test the predictions of the theory by adjusting the initial conditions so that one equilibrium is selected to see which equilibrium is easier to displace by means of mutations. In particular, at the beginning of the experiment the subjects are asked to play ten rounds of a pure coordination game. During the pre-play rounds the players were expected to converge to one of two possible equilibria, thereby to constitute a convention. After the pre-play rounds, a new strategy is added to the game.

Given the literature reviewed in the first chapter, an existence of a powerful convention may affect people's attitude to changes and probability to adopt a new option (see Young, 2003; Bicchieri, 2006). I suggest that the existence of the established standard makes players less willing to switch to another strategy, even when it is efficient. This conjecture is driven by the presence of network effect in the payoffs structure of the experimental game. It emphasizes the dependence of each player's payoff on the number of other players choosing an identical strategy. A switch to a new equilibrium should pass a critical mass threshold in order to be profitable. Given players expectations to uphold the equilibrium established earlier, it is of one's best interests to uphold these expectations, unless he is sure that a significant number of players will also deviate. On the other hand, an absence of a standard choice does not bind players to any particular game strategy and an introduction of a new option, especially if it provides a riskless solution to a coordination problem, seems to be a good reason to adopt it.

Thereby, the first hypothesis aims to test the influence of the previous events on the possibility of technological lock-in. Namely, it analyzes if the strength of the existing convention affects the adoption of the newly introduced strategy.

H1: The coordination rate achieved in the pre-play period influences the adoption process in the subsequent rounds. In particular: low coordination rate in the pre-play rounds promotes adoption while high coordination rate supports lock-in.

The introduction of a new technology to the game where there already exists an established standard helps out investigating population's transitions from one equilibrium state to another. If the players are conditioned to choose a conventional strategy, appearance of a new strategy may serve as noise in stochastic models that affects the long-run equilibrium selection. In my experiment I consider two cases: when the newly introduced strategy is payoff-dominant relatively to the incumbent one and when it is ½ dominant. Advantages from a new payoff-dominant strategy, may appear more obvious to the players after being in a relatively inferior state. The introduction of a payoff-dominant strategy is expected to attract the attention of the players towards the new payoff-dominant equilibrium and its eventual adoption. On the other hand, after achieving coordination on an efficient equilibrium a transition to the ½ dominant equilibrium that would cause disadvantages in players' payoffs seems less likely (see also Corbae and Duffy, 2008). In this way, while an incompatible but advantageous technology, which is introduced after an establishment of a conventional choice, attracts players, a well-compatible technology represented by a ½ dominant strategy may be ignored. An experimental confirmation of this assumption would support the model with state-dependent mutations (Bergin and Lipman, 1996) in which the probabilities of players making a mistake and playing a strategy different from the best-response, which is an execution of a newly introduced strategy, depends upon players' satisfaction from the state where they are located. For instance, agents are more likely to make a mistake towards a more efficient strategy than otherwise.

H2: When the established equilibrium is Pareto-efficient, and the newly available technology corresponds to the ½ dominant strategy (and gives a lower payoff respectively), players do not switch to it and remain at the conventional efficient equilibrium.

H3: When the established equilibrium is ½ dominant but inefficient, players switch to a newly available payoff-dominant strategy even if it is more risky.

Moreover, testing these two hypotheses checks the consistency of the individuals' behavioral patterns. It allows investigating whether the properties of the conventional equilibrium affect the final convergence: if the players' choices are consistent they have to converge to the same outcome whenever the established equilibrium was payoff-dominant or ½ dominant.

The main peculiarity of this experimental design is that the fluctuations provoked by the introduction of a new technology naturally challenge the stability of the established equilibrium without a need of exogenous shocks and speed up the convergence process. The transitions from the established convention serve as a way of testing theoretical predictions about equilibrium selection in coordination games. A convergence to the same (payoff-dominant or ½ dominant) equilibrium from different initial points would imply disprove the role of path-dependence process in determination of the direction of social development.

Therefore, the *forth* hypothesis is as follows:

H4: The selected equilibrium will only depend on initial conditions

The current experiment includes testing of all the hypotheses above in two different matching structures: global and local. As it has been discussed earlier, different interaction network may result in different outcomes. Contrast to the theoretical prediction of Ellison's (1993), players arranged on a circle and interacting only with their direct neighbors were observed to converge to the efficient equilibrium in a number of experiments (Berninghaus et al. 2002; Cassar, 2007; Barrett et al., 2011). This could be explained by repeated games effect that is by the fact that a local network allows the participants to influence their partners' choices and respectively adapt their own strategies, which is impossible in random matching. Thereby, it is expected that in the local matching treatments the rate of playing the payoff-dominant equilibrium will be higher than in the global matching.

H5: The rate of payoff-dominant choices is higher in the local matching interaction structure than in the global matching.

2.5 Experimental design

In this section I describe the procedures implemented in the experimental sessions. The first step of the experiment was common for all the treatments: participants were asked to play the simple coordination game in Table 3. In that game, *a* is the utility of technology *A* and *B*. Throughout the experiment *a* is fixed and equal to *40*. The AB-game has two pure strategy Nash equilibria *(A,A)* and *(B,B)*. Related experimental research showed that in pure coordination games with one population after few rounds of interactions players usually tip to one of two pure strategy Nash equilibria rather than playing a mixed strategy equilibrium (Hossain and Morgan, 2009; 2011, Friedman et. al 2011). It was expected that individuals would converge to equilibrium *(A, A)* within little time. The reason for this assumption is the research on focal points that posits that the strategy labels can influence the result in coordination games. (Sugden, 1995; Mehta et al. 1994a; Crawford et al., 2008). Although strategy A yields the same payoff as B, in the current game it is focal. First of all label A is more salient relatively to B as the first letter in the alphabet. Second, in the normal form game AB A is a top left strategy, which makes it focal also for its primary position. All these together affects individuals' pre-reflective perception of strategy A making it stand out from another possible choices, and therefore most likely to be selected.

	A	B
A	a, a	0, 0
B	0, 0	a, a

Table 3. Pure Coordination Game AB

Each experimental session involves interaction of two independent groups of 10 players. After each round of interaction, the players were presented a distribution of choices in their group and average payoff for each choice on the computer monitor. The picture 1 in the Appendix A represents the players' game screen and available information.

After ten rounds, a new strategy, which represents the introduction of a new technology, was added to the game (Table 4). Depending on the parameters of the treatment, the newly introduced strategy was more efficient than the status-quo strategies (strategy C) or less efficient but ½ dominant (strategy C*). Parameters *b* and *c* in the payoff table represent the compatibility of the technology C (C*) with the technologies *A* and *B* and parameter *d* is the advantage (d>a) or disadvantage (d<a) of the technology C (C*). During the game, the players made choices in both cases when the added strategy was payoff-dominant (game ABC, table 5) and when it was ½ dominant (game ABC*, table 6). The restrictions that were put on the parameters were: $a>b$, $d>c$, and $(a-c) > (d-b)$. Under these conditions the ABC-game (ABC*) has three equilibria: *(A,A), (B,B)* and *(C,C) (C*,C*).*

	A	B	C (C*)
A	a, a	0, 0	b, c
B	0, 0	a, a	b, c
C (C*)	c, b	c, b	d, d

Table 4. Introduction of the 3rd Strategy

Assume that the initially selected equilibrium is *(A,A)*. Then, the players shall stay within the basin of attraction of the *(A,A)* equilibrium if the payoff from playing strategy A is larger than the payoff of playing strategy B or C:

$\Pi_1(p) = ap_1 + bp_3 > \Pi_2(p) = ap_2 + bp_3$

$\Pi_1(p) = ap_1 + bp_3 > \Pi_3(p) = cp_1 + cp_2 + dp_3$

where p_1, p_2 and p_3 are the proportions of the population playing strategy A, B and C respectively; while $\Pi_1(p)$, $\Pi_2(p)$, $\Pi_3(p)$ – is the payoff from playing strategies A, B, and C respectively.

Let us consider transitions between equilibria that only involve mutations in one strategy, which is A. The only possible transition is a switch from *(A,A)* equilibrium to (*B,B)* or to *(C,C)*. To study a switch to (*B,B)* we set $p_3 = 0$ and solve the equalities above for p_1 and obtain:

$p_1 > p^{(B,B)} = 1/2$;

$p_1 > p^{CB} = c/a$;

where p^{ij} is the he number of mutations required to leave *(A,A)* by having subjects switch to strategy *i*, and mutants playing strategy *j.* The necessary proportion of mutants needed to escape from *(A,A)* towards *(B,B)* when the mutants are playing strategy B is ½. The necessary proportion of mutants needed to escape from *(A,A)* towards (*C,C*) is *c/a.* If an escaping from *(A,A)* towards *(B,B)* requires less mutations than escaping *(A,A)* towards *(C,C),* the transition towards *(B,B*) will occur.

If we consider the transitions of individuals from *(A,A)* only to *(C,C),* we set $p_2=0$ and solve the equations above:

$p_1 > p^{CB} = 0;$

$p_1 > p^{CC} = \frac{d-b}{a-b+d-c}$;

Notice that the first condition is always true, which makes sense because there cannot be a transition out of *(A,A)* towards *(B,B)* when all individuals play either *(A,A)* or *(C,C)*. So in this case the only transition can be towards *(C,C)*.

The ratio $p^{*}=\frac{d-b}{a-b+d-c}$ is the critical mass needed to switch from one equilibrium to another. It determines a sufficient share of population needed to adopt a particular strategy such that every subsequent adopter is better off by choosing it rather than choosing any other strategy. So that if C is the new technology, the p^{*} is the share of players adopting C such that the payoff that gives C is greater that the payoff of A. The larger is the critical value – the more mutation it takes to escape the basin of attraction of its equilibrium and to transit to another one. In other words, the larger is the critical value the more people are required to switch away from the old equilibrium and to adopt a new one.

If $p^{*} < ½$ then the equilibrium is ½ dominant: it has a larger basin of attraction, requires more mutations to escape from it and less than ½ of the share of adopters to become more profitable comparing to another one. If $p^{*}>1/2$ then the equilibrium is payoff-dominant: it has a smaller basin of attraction, requires few mutations to escape from it and more than ½ of population to adopt it in order to be more profitable. Notice, that in the games against the whole population, the ½ dominant strategy is always the best response if the distribution of individuals' choices have equal probability.

2.5.1 Treatments of Global Matching

In the global matching treatments, participants play against their group as a whole and their payoffs are calculated according to the standard formula for these kind of interactions described earlier in the section 2.3.1. The global matching protocol involves two treatments called ABC and ABC*, which differ between themselves in the order of how the new strategies are introduced. First, I explain the ABC treatment, where a new strategy introduced after ten rounds is payoff-dominant (see table 5, where a=40, b=32, c=0, d=45).

	A	B	C
A	40, 40	0, 0	32, 0
B	0, 0	40, 40	32, 0
C	0, 32	0, 32	45, 45

Table 5. Introduction of a Pareto Dominant Strategy. Game ABC

The basins of attraction of the ABC game are illustrated on the Figure 3. As you can see, the basin of attraction of the payoff-dominant equilibrium *(C,C)* is smaller than the basins of attraction of the ½-dominant equilibria *(A,A)* and *(B,B).* As it was calculated earlier, the basins of attraction of the *(A,A)* and *(B,B)* equilibria are of equal size and require equal number of mutants, which is 50% of the players, to transit from one basin of attraction to the other. An escape from any of these equilibria to the basin of attraction of the equilibrium *(C,C)* would require a mutation towards strategy C of more than 75% of population. To escape from the payoff-dominant basin of attraction of the equilibrium *(C,C)* is also easier. It takes 25% of mutants towards *(A,A)* or *(B,B)* separately or 20% of mixed mutants. According to the predictions of evolutionary models, the selected equilibrium is the one with the largest basin of attraction, since it requires less mutations to be transferred to from another basin of attraction. Therefore, in the present game, an evolutionary approach suggests the selection of either equilibrium AA or equilibrium BB in the long run.

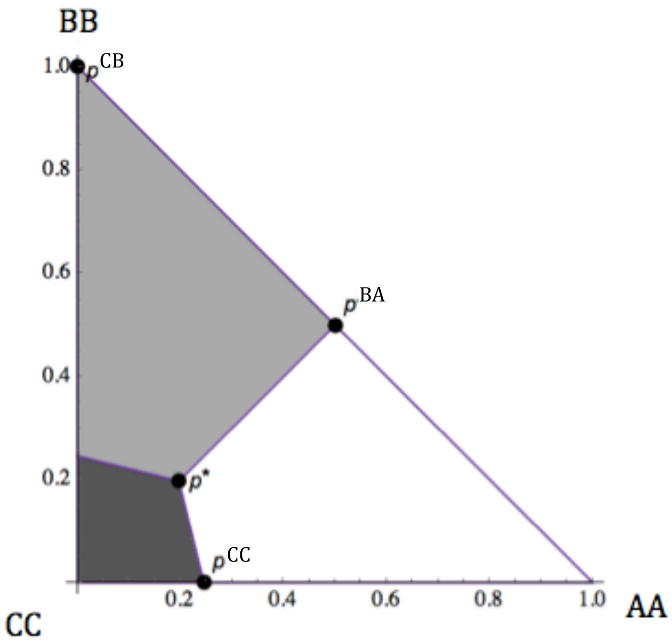

Figure 3. Basins of attraction of the Game ABC

The introduction of the payoff-dominant strategy C represents a technological innovation that is more efficient than the technologies A or B for its consumers. However, strategy C is more risky than A and B, i.e., technology C is incompatible with the previous standards and could not be used together. Therefore, players have to choose whether to remain playing a conventional old technology *A* (or *B*) or switch to the new and more efficient strategy *C* and face a risk to be the only one adopter of an incompatible technology and consequently receive a zero payoff. Given the established beliefs of the players about the future actions of their co-players, the introduction of an advantageous technology C tests the theoretical predictions about the power of a historical precedent as a coordination device and a possibility of a technological lock-in.

In order to test whether the individuals' preferences on the risk/payoff dominance are robust, in the same treatment (ABC) in the rounds 21-30 I replace the payoff-dominant strategy C with the ½ dominant strategy C* (see table 6, where a=40, b=0, c=28, d=36). The basins of attraction that are formed by the introduction of the ½ dominant strategy C* are illustrated in Figure 4. Now there are two small payoff-dominant basins of attraction of the equilibria *(A,A)* and *(B,B)* and one large risk-dominant basin of attraction of the equilibrium *(C*,C*)*. However, the amount of mutation needed for transitions from one equilibrium to another are equal to ABC-game. As before, an escape from the basin of attraction of the risk-dominant equilibrium requires 75% of mutations towards *(A,A)* or *(B,B)*. The minimum number of mutations needed to escape either of the payoff-dominant basins of attractions, *(A,A)* or *(B,B),* is as well 25% of population. Therefore, since all the proportions have been saved, the final outcome of equilibrium selection according to the theoretical predictions should also be the same, that is a convergence to the ½ dominant equilibrium CC, which has the largest basin of attraction.

	A	B	C*
A	40, 40	0, 0	0, 28
B	0, 0	40, 40	0, 28
C*	28, 0	28, 0	36, 36

Table 6. Introduction of a Risk-Dominant Strategy. Game ABC*

The strategy C* represents a technology, which is less efficient than the existing A and B technologies, but compatible with them and gives a positive payoff independently on the choices of other players. The technology C* is partially compatible with old A and B and its consumers are not risking to loose much by switching to it. However, mutants "pay" for such security level, receiving a payoff, which is smaller than the incompatible technologies *A* and *B* yield. Note, that C* is compatible with the technologies A and B unilaterally. In terms of technological adoption this would mean that a new technology C* is compatible with the old A and B and its users may enjoy the network benefits of products A (B) but not otherwise. For instance, a one-way compatible technology A (B) could be represented by a software that does not read files created in format *.ccc,* but only in format **.aaa (*.bbb).* In the same time software C* allows reading files created in all of the formats: *.aaa, *.bbb and *.ccc. Therefore the users of A (B) software can only exchange files *.aaa (*.bbb) with another users of the same standard, while the users of C* may freely use their compatible software for working with any other standard and profit from the network of its consumers.

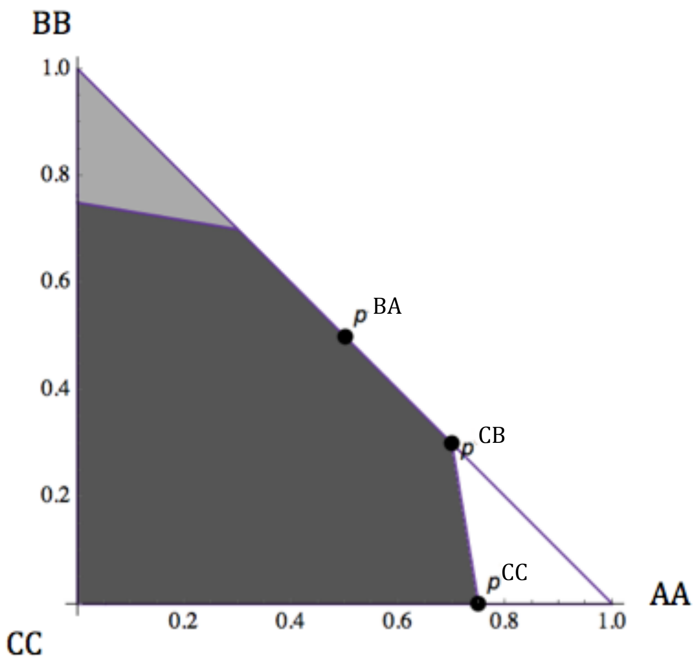

Figure 4. Basins of Attraction of the Game ABC*

With the introduction of C*, an absence of the payoff-dominant strategy C deprives the players of their coordination tool if has become a conventional choice during the last rounds. Therefore, two game scenarios are possible: either players switch back to the earlier standard constituted at the very beginning of the game (A or B) or choose the strategy C*. The former case would justify the robustness of their choices in following a payoff-maximizing rule, and the later one would provide evidence that for achieving coordination people rely on option's focality rather than payoff advantages. In the case when during the rounds 21-30 ½-dominant strategy A (or B) was a conventional choice, a similar logic is used for analyzing players' behavior after the game modification. The replacement of the strategy C with the strategy C* makes A and B loose their risk-dominance power, and hence rational players should switch to C* in order to play ½-dominant strategy as earlier. A continuation of playing a conventional A (or B) strategy after an addition of C* is likely to be caused by lock-in rather than by the preference for payoff-dominance: the players could have adjusted their choices earlier after an introduction of a payoff-dominant strategy C, but this did not occur.

The ABC* treatment is practically the same as the ABC treatment apart from the order in which new strategies are added to the game. For the ABC treatment, after 10 rounds of the pre-play, the payoff-dominant strategy C is introduced first and after 10 rounds and exchanged with the ½-dominant C* for another 10 rounds. For the ABC* treatment, after the pre-play rounds, the C* is added first for the 10 rounds and then replaced with C for another 10 rounds. Therefore, the participants of the ABC treatments played the following sequence of the game: 1-10 rounds – AB game, 11-20 rounds – ABC game, 21-30 rounds – ABC*; while the participants of the ABC* treatment played the game in the opposite order: 1-10 rounds – AB game, 11-20 rounds – ABC* game, 21-30 rounds – ABC game.

For both treatments, after each round of the game, each participant received a feedback about his payoff, and about the payoffs and the actions of the other players in the group. Players were also aware of the total length of the game (30 decisions), but did not know in which treatment they were participating. Note, that in the beginning of the game, the instructions given to the participants did not stress the choice between 2 or 3 possible strategies and but teach to calculate their payoffs in a general form.

2.5.2 Treatments of Local Matching

The local interaction sessions, as well as the global treatments, consist of two treatments: ABC and ABC* treatments. These treatments replicate the same procedures of the introduction of new strategies as in the global matching protocol but differ in matching method and the payoff function. In these sessions, I explore how changing the matching method from global to local may affect agents' coordination behavior. As before for each session, 20 players are randomly assigned into two groups of equal size. However, now players in each group are located on a circle and during the game were matched only with two of their neighbors (one on the left and one on the right) in a random order during all 30 rounds of interactions. In a local network, each player's interaction neighborhood overlaps with the neighborhood of the one's partner, however, each player remains isolated from the players located far away in the circle. The position of each player on a circle remains constant through the entire game. The players are told that during the game they are matched with one of the players in their group but they are not informed of the used network structure[4]. The payoff function of the players in the local interaction protocol is not averaging the payoff from all the players executing the same

[4] This is done intentionally, as a typical practice for the experiments that study coordination in different matching structures (see Cassar, 2007). Unknowing the matching mechanism serves as a method to avoid biases caused by players' preconceived ideas about how they can influence the behavior of their neighbors.

particular strategy. Instead, they receive the payoff that exactly corresponds to the intersection of their choices in the game matrix.

As in the global matching sessions, in the local matching sessions the participants of the ABC treatments played the following sequence of the game: 1-10 rounds – AB game, 11-20 rounds – ABC game, 21-30 rounds – ABC* game, The subjects of the ABC* treatments played the game in the opposite order: 1-10 rounds – AB game, 11-20 rounds – ABC* game, 21-30 rounds – ABC game. All other game characteristics were held the same.

2.6 Pilot sessions

Before running the experiment itself, a pilot session for the global protocol of the ABC treatment was conducted. For the pilot session, twenty participants were randomly assigned into 2 groups of 10 players, where they remained for the 50 rounds of the game. As the treatment ABC intended, for the first 10 rounds the players chose between two strategies labeled A and B, for the rounds 11-20 they chose between three strategies labeled A, B, and C and for the rounds 21-30 – between the strategies labeled A, B, and C*, then again A, B, C for the rounds 31-40; and A, B, C* for the rounds 41-50. The outcome of the pilot session explicitly showed that labeling the strategies in alphabet order A, B and C (C*) appeared to be very salient. Right from the first round of the game, all of the players in both groups chose the strategy labeled A. The choice of strategy A as a coordination device was also provoked by its top left position in the payoff matrix. A high coordination rate persisted during all the game rounds. 100% of coordination on strategy A lasted through all 10 rounds of the pre-play, in exception of a few players who once tried to play a strategy B but immediately switched back to A. On the 11th round after an introduction of a more efficient strategy C, 45% of the players switched to it immediately, while its full adoption took 3 rounds on average. The proportion of adopters went lower than 80%. As soon as a payoff-dominant strategy C was replaced by a risk-dominant strategy C*, 50% and 80% of the players in the first and the second groups switched back to the old equilibrium *(A,A),* which now has become relatively more efficient than *(C*,C*).* After two rounds of interaction, coordination on equilibrium *(A,A)* has reached the level of 100% in both groups. In the second adoption experience in the rounds 31-50, the transition to the most efficient equilibrium was even faster (see graph 1 in the Appendix A).

The evidence of the pilot experiment clearly demonstrated that subjects choose the most efficient alternative if the game has salient labels and coordination task is facilitated with the presence of focal points. In this case, the convergence to inefficient equilibrium, and even more the lock-in event, is practically impossible. The pilot participants did not experience a problem of misccordination and thanks to the salient labels earned high payoffs right from the beginning of the game. However, since one of my hypotheses tested if the strength of the equilibrium established at the pre-play affects further development of the game, I decided to complicate the coordination task. For this reason, for the experiment sessions the names of the strategies A, B, C and C* were replaced with neutral labels "$", "@", "&" and "#" respectively. Moreover, the order in which they appear in the payoff matrix was changed randomly each round to avoid a positional salience. The number of interaction rounds was cut to 30 since the second time of the introduction of the same strategies demonstrated practically the same result as the first one.

In fact, such perturbations changed crucially the levels of coordination; not only in the pre-play rounds but also in the further play. Presumably, without a focal strategy, the participants contributed more effort in the establishment of a conventional equilibrium. Therefore, a shift away from such a valued equilibrium, although inefficient with the introduction of a new strategy, happened to be more difficult. However, I will talk about it more precisely in the next section. Note, that further in the chapter I still call the strategies A, B, C, and C* for purposes of exposition.

2.7 Results

In this section I discuss the experimental findings providing a detailed discussion of each hypothesis and related results. The graphs 2-5 in the Appendix A show the differences in people's behavior among treatments and demonstrate the main tendencies in technological adoption under different conditions. Further in the analysis a technology will be considered successfully adopted if the strategy that represents it is executed by at least 75% of the population.[5] The measurements of coordination (adoption) rates according to which I evaluate the experimental hypotheses are taken on the 10th, 20th and 30th rounds. Where the 10th round is the last pre-play round and 20th and 30th rounds are the last rounds of the game modification caused by an introduction of a new strategy. In this way, players have 10 rounds of interactions to reconsider their strategies after an introduction of a new one (as in Corbae and Duffy, 2006). In the cases where the adoption rate is exactly equal to 75% also the result of coordination in the antecedent round is taken into account: a strategy is said to by adopted if it is more than 75% and not adopted if less. I also take into a consideration the general tendency of the adoption rates during

[5] This threshold has already been used in a literature calculated as an average percentage of market share needed to define dominance and lock-in (Meyer, 2011). According to the European Court of Justice, 50% of a market share is considered to be an evidence of market dominance (European Court 1991) and lock-in is defined as 90% of market share (Shapiro and Varian; 1999).

the game rounds, however, in most on the cases it concurs with the outcome of the last round.

The experiment was run in June 2014. In total 136 students from various faculties of the University of Trento took part in the experiment and the pilot sessions. In order to find subjects, an advertisement of a brief description of the event was posted via emails, which stressed monetary payoffs. The experiment was written in the Z-tree software (Fischbacher, 2007). The experiment consisted of seven sessions, four of which were the sessions of global matching and 3 were the local matching sessions[6]. Each session included 2 treatments: ABC or ABC* either of global or local network structure. Due to the low turnout at the experiment, most of the treatment groups consisted of 8 players instead of 10 as it was expected. The summary of the experimental sessions and the number of players per each is presented in the table 1 of the Appendix A.

At the beginning of each session of the experiment, participants received the game, which were read aloud. Moreover, we asked the subjects to answer in a written form three simple questions about the game they were about to play to make sure that they understood the rules. The experiment started only after all the participants gave the correct answers to the questions. Obviously, no communication between participants was allowed during the sessions.

Each experimental session took about an hour of time. According to the session length the theoretical maximum that could be earned by a player was calculated to be 11 euros plus a show-up fee of 3 euros. The conversion rate was 0.009 euros for one token (9 euros for 1000 tokens). In the end of the experiment, participants exchanged their earned experimental tokens to euros. The students were

[6] One of the sessions that was intended to consist of two ABC* treatments of local matching was replaced by the pilot session and eventually was omitted.

paid the reward privately in cash. The average earnings of the participants including the show-up fee were 11.4 euros.

Now, let us turn to the exploration experimental hypotheses, which I requote below.

Hypothesis 1: The coordination rate achieved in the pre-play period influences the adoption process in the subsequent rounds. In particular: low coordination rate in the pre-play rounds promotes adoption while high coordination rate supports lock-in.

Due to the lack of the control sessions where the players would choose a technology without participating in the pre-play AB-game, it is impossible to estimate the effect of the presence of the convention by itself. Instead, the convergence rates during the AB pre-play rounds were tested.

The coordination rate achieved by the end of the pre-play AB-game with neutral labels was quite high. Contrast to the pilot session, with the neutral names of the strategies and their relocation on the monitor of the players, the coordination rate on the 10^{th} round of interactions has reached 75%, i.e. the convention has been established, in 5 out of 8 cases in the global matching network and in 4 out of 6 cases in the local matching treatments (see tables 2-5 with the experimental data in the Appendix A)

Without a focal strategy, in the treatments ABC of global matching network, when the newly introduced strategy was more efficient, its further adoption was observed to be more difficult than in the pilot sessions. The correlation between the maximum adoption rate on the 10^{th} round of the pre-play and the coordination rate on the newly introduced strategy C on the 20^{th} round is -0.29 for the groups 1, 2, 3, 4. Therefore, there is a slight evidence that the more powerful is the convention established at the pre-play the harder would be to break it. However, the outcome of the pilot session suggests that if the convention at the pre-play has been attained easily without effort and series of attempts, it would be easy to brake. In that case, subjects transferred easily to the new efficient strategy and switched back when the environment changed.

The lowest coordination rate during the pre-play rounds (AB-game) was observed in the sessions 3-4 of global network of the ABC* treatments, which was 61.75% on average between groups 5-8 contrast to 81.25% on average between groups 1-4 of the ABC treatments. However, the newly introduced ½ dominant strategy C* was adopted in all of the ABC* treatments by the 20^{th} round. Negative correlation coefficient (-0.5) between the average coordination rate over the pre-play in groups 5-8 and the adoption rate of ½ dominant strategy C* on the 20^{th} round – after ten interaction rounds – suggests that switching to it resolves the coordination problem that players experienced in the pre-play. However, transitions to a newly introduced strategy as a method to overcome low coordination were not observed in other treatments neither in local nor in global interaction structures.

All together, for the global matching networks, the Mann-Whitney test did not show significant difference between the adoption rates of a newly introduced strategy C or C* formed by the 20^{th} round between the groups that established a convention by the end of the pre-play (groups 1, 3, 4, 5, 8) and those who did not (groups 2, 6, 7); ($z = 1.200$). Therefore, hypothesis 1 is rejected. However, the experimental evidence of the pilot session provides us with an intriguing insight: low coordination rate may cause a switch to the newly introduced risk-dominant technology but not otherwise; a high coordination rate was not observed to support lock-in neither on risk-dominant or payoff-dominant equilibrium. The coordination rate achieved during the pre-play period, in majority, does not influence further technology adoption process, unless this technology is compatible with the incumbent ones and players had coordination problems in the pre-play rounds.

H2: In the games where the newly available technology corresponds to the risk-dominant strategy (and gives a lower payoff respectively), players do not switch and remain choosing the conventional efficient equilibrium.

The risk-dominant strategy C* in the ABC treatments was introduced on the 21st round while in the ABC* treatments it was introduced in the 11th round. The initial adoption rate in the global matching network was observed to be 40.6% on average among groups 1-4 in the ABC treatment. After ten rounds of interaction the risk-dominant strategy C* was adopted in three out of four groups and its average adoption rate has reached 71.9%.

During the pre-play rounds in the ABC* treatments, despite a conventional equilibrium has been finally selected in 2 out of 4 groups by the end of 10th round, players experienced difficulties with coordination and fluctuated from one strategy to another in all of them. After the introduction of the risk-dominant strategy C* on the 11th round in the ABC* treatments, 48.1% of the players on average in four groups have adopted the newly introduced strategy C*. By the 20th round, the average adoption rate of the risk-dominant strategy has increased to 91.9%. Such high coordination rate on the risk-dominant equilibrium may be explained as players' way of solving the coordination problem that they experienced in the pre-play rounds. The coordination rate between two strategies in the ABC* treatments was on average 61.25% during pre-play periods which is about 20% less than in the ABC treatments. It is possible to assume that an introduction of the third option might have served as a focal option that worked as an instrument of coordination.

The opposite tendency was observed in the local network treatments. In the ABC treatments the average percentage of initial adoption of the newly introduced risk-dominant strategy C* on the 21^{th} round was 31.25% between groups 9-12. During the subsequent rounds this percentage fell down to 18.75% and the population has returned to the conventional payoff-dominant strategy that has been selected during the pre-play rounds. However, given the experimental data, it is difficult to disentangle the effect of easiness or the difficulty of pre-play coordination on one hand and the differences in adoption rates after an introducing payoff-dominant or ½-dominant strategy on another hand. Such disentangling would be feasible if the players of the ABC* treatments would have coordinated on one of the options during the AB-game, which would require more experimental sessions. Another possibility would be to consider the periods 11-20 of the ABC treatments as a pre-play before the introduction of the risk-dominant strategy C* on the 21 round. Yet, despite these periods demonstrate a tendency of subjects to coordinate on one of the game strategies, the achieved coordination rates could hardly be called conventional equilibria and used for the future analysis.

In the ABC* rounds, after the introduction of the risk-dominant technology C* on the 11^{th} round, 18.7% of players on average in groups 13-14 switched to playing it. After ten rounds of interaction, this percentage has fallen down to 12.5%

Given the results of experiment, we can reject the second hypothesis for the global interaction networks, where the experimental evidence supports the adoption of the risk-dominant technology. However, for the local matching networks, experimental data supports the second hypothesis.

H3: When the established equilibrium is ½ dominant but inefficient, players switch to a newly available payoff-dominant strategy even if it is more risky.

The payoff-dominant strategy C was introduced to the game on the 11th round in the ABC treatments and on the 21st round in the ABC* treatments. The experimental data showed that in the global matching network the adoption rates of the payoff-dominant technology are different treatments in ABC and in ABC*. In the ABC treatment of the global matching, the percentage of initial adopters of the newly introduced strategy C was on average 62.5% between groups 1-4. However, this coordination rate had a clear decreasing tendency in all of these groups: it fell down to 34.5% by the 20th round of the game. Such fluctuations also could be explained by a novelty effect – people momentary enthusiasm towards everything new. Surprisingly, in three out of four groups the players started to switch back to the risk-dominant equilibrium established at the pre-play after the new payoff-dominant strategy C has already accumulated the number of adopters needed to make it a best-respond, which lasted several rounds.

The opposite tendency was observed in the ABC* treatments of the global matching, when the payoff-dominant strategy was introduced on the 21st round after the players in all the groups converged to the payoff-dominant strategy. The initial coordination rate on the newly introduced strategy C was 67.5% on average between groups 5-8 and after ten rounds of interaction it has reached 83.1%, which indicates its adoption. However this could be explained by a low coordination rate during the AB rounds, which coincidently happened in all the ABC* treatments. It is likely that the players choose the newly introduced strategy because of its salience due its being the last introduced option, which is of course independent from its risk/payoff properties. Altogether, such divergence in adoption patterns among treatments, which differ only in the order in which the new strategy was introduced, signifies that the adoption process has not Markov property, since the result depends on the past actions.

In the local matching treatments a different development scheme was observed. The adoption of the payoff-dominant technology C had similar patterns in the treatments ABC and ABC*, despite its introduction on the different rounds. After its introduction on the 11th round in the ABC treatment, its initial adoption rate was 87.5% on average between groups 9-12. During the next periods it kept growing and after ten rounds it has reached 96.9%. In the ABC* treatments, coordination on the payoff-dominant strategy introduced on the 21st round had an increasing tendency as well. The coordination rate on the strategy C grew from the 56.25% on the 21 round to the 87.5% on the 30th round of interaction on average in groups 13-14 and consequently a new payoff-dominant equilibrium was constituted.

Therefore, the third hypothesis concerning the transition to the payoff-dominant strategy after a condition on the conventional risk-dominant equilibrium is rejected for the global matching but cannot be rejected for the local interaction network. The initial fluctuations towards the payoff-dominant strategy in the global matching treatments can be described as a novelty effect, which, however, is not enough to determine the adoption a new technology.

H4: Initial conditions determine further equilibrium selection

Stochastic models of equilibrium selection are based on the hypothesis that noise in decision-making is "small". In some variants of these models is also assumed that only one player at the time can mutate. Jumps from one equilibrium to another are the consequence of the accumulation of many of such independent "mutations". The experimental evidence showed that after the appearance of a new option, mutants are always more than one (or a few). Possibly because of the novelty effect, there is always at least 30% of the players that deviate right after they face a new option. Therefore, the adoption occurs rather through jumps than trough smooth mutation described in the theoretical models (KMR, 1993; Ellison, 1993; Young, 1993).

The experimental evidence has confirmed the theoretical predictions about the extreme importance of the initial conditions for the further development of the game. In all of the ABC treatments after the introduction of the payoff-dominant strategy C, its adoption rate was quite high: on average 62.5% in the global treatments and 87.5% in the local treatments. However, the percentage of deviators from the status-quo strategy needed for the successful adoption of the newly introduced payoff-dominant strategy was designed to be more than 75%. Given that, further convergence to the payoff-dominant strategy did not occur (the correlation coefficient between the adoption of a new strategy on the 11^{th} and 20^{th} round is 0.5488). In contrast to global networks, in the local networks, this threshold was passed and hence the strategy has been adopted. Thus, the experiment provided evidence that if the strategy does not accumulate the required percentage of mutants it cannot leave the basin of attraction of the incumbent equilibrium.

This tendency was also observed in the ABC* treatments. In all of the groups of the global networks, the initial coordination on the newly introduced risk-dominant strategy was higher than 25%, which is the percentage of adopters necessary to make a new strategy more profitable than the incumbent ones. Hence, in the subsequent rounds, in line with the predictions of the KMR model (1993), the ½-dominant strategy has been adopted. The local matching ABC* treatments also support these theoretical predictions. The initial coordination on the newly introduced strategy C* of players was less or equal to 25% in all of the groups and, consequently, it has not been further adopted by the players.

Now, lets consider rounds 21-30 when a new strategy was repeatedly introduced to the game. The results of these rounds are more ambiguous, probably, because the second introduction of a new strategy brought more dynamics to the game and made players more enthusiastic towards changing a strategy. For the ABC treatments, the strategy C*, introduced on the 21 round, was risk-dominant. In the global matching networks, in three out of four groups the initial adoption rate of the strategy C* was more than 25% - the minimum percentage required for the adoption of the risk-dominant strategy. In these groups the coordination on the risk-dominant strategy grew from 54% in the 21st round to 95.8% by the 30th round of the game. In the group 3 the players did not react at all on the introduction of the new strategy and the rate of coordination on it was constantly zero during the rounds 21-30. This pattern clearly demonstrates the game's dependency of the initial conditions. This dependency was not observed in the local matching protocol, though. In the 21-30 rounds, risk-dominant strategy C* was not adopted by neither group independently of the initial conditions. Therefore, the experimental evidence suggests that the initial conditions determine further equilibrium selection in global networks is while in local matching the crucial factor of equilibrium selection is the payoff-dominance of a strategy.

In the ABC* treatments in the global network in the rounds 21-30 after the introduction of the payoff-dominant strategy C its initial adoption rate was on average 67.5%. However, independently from the initial conditions, the players converged to the payoff-dominant strategy C. Its coordination rate by the end of the 30th round reached on average 83.25% in groups 5-8. However, as it has been said earlier, the coordination on the payoff-dominant strategy can be considered exceptional since players experienced coordination problems in the pre-play rounds. As a consequence, their coordination on the newly introduced payoff-dominant strategy is probably better explained in terms of salience. In the local matching treatments, the initial coordination rate on the payoff-dominant strategy C was on average 43.75% between groups 13-14. Although it was less than the proportion needed for a successful adoption, which is 75%, by the 30^{th} round it has been adopted with an average coordination rate 87.5% between groups. This suggests that independently of the initial conditions, players converge to the payoff-dominant equilibrium.

The table below summarizes the results. In the *local matching networks*, even when the initial conditions were in favor of adoption of a risk-dominant strategy, the players consistently converged to the payoff-dominant equilibrium. On the other hand, in the *global matching networks*, in the majority of the cases the population converged to the risk-dominant equilibrium. However, the convergence to the risk-dominant equilibrium could be determined by initial location of the population in its basin of attraction. This is the reason why it is difficult to distinguish which factor had a greater influence, risk-dominance or population's initial condition, since in these treatments these two factors of equilibrium selection go inline. Therefore, the fourth hypothesis that assumes that the initial conditions determine further equilibrium selection is rejected for the local matching but cannot be rejected for the global matching treatments.

Newly Introduced strategy	Global Matching	Local Matching
$1^{\text{st adoption}}$ of Payoff-dominant		
$1^{\text{st adoption}}$ of Risk-dominant		
$2^{\text{nd adoption}}$ of Payoff-Dominant		
$2^{\text{nd adoption}}$ of Risk-dominant		

Table 7. Equilibrium Selection Principle

denotes that the equilibrium selection factor is risk-dominance and it coincides with the initial conditions;

denotes that the equilibrium selection factor is payoff-dominance and it coincides with the initial conditions;

denotes that the equilibrium selection factor is payoff-dominance and it does NOT coincide with the initial conditions;

In addition, I also report the data about the switching behavior during the experiment by calculating the probability that the final state lies in the same absorbing basin as the initial state of the population. As it has been said earlier, the basins of attraction of the risk-dominant and payoff-dominant equilibria were modeled to be ¼ and ¾ respectively. The theoretical transition probabilities between the basins of attraction are given in the table below, which indicates the initial and final state of the population (Table 8). Notice, that I consider not the technology adoption but rather the location of the population in the basin of attraction of the particular technology. The experimental transition probabilities are a bit different from the calculated ones. Contrast to the global network where the experimental switching probabilities slightly differ from the theoretical ones in favor of risk-dominance; in the local network they diverge extensively. The experimentally estimated transition probabilities for the local network suggest that the switches are very likely to occur from the risk-dominant basin of attraction towards the payoff-dominant, while the opposite transition has never been observed (Table 9).

from\to	Risk-dom.	Payoff-dom.
Risk-dom.	0.75	0.25
Payoff-dom.	0.25	0.75

Table 8. Theoretical Transition Probabilities

from\to	Risk-dom.	Payoff-dom.
	Global Matching	
Risk-dom.	10/12 = 0.83	2/12 = 0.16
Payoff-dom.	2/4 = 0.5	2/4 = 0.5
	Local Matching	
Risk-dom.	2/6 =0.33	4/6 =0.67
Payoff-dom.	0/6 = 0	6/6 =1

Table 9. Experimental Data on Transition Probabilities

H5: The rate of payoff-dominant choices is higher in the local matching networks than in the global matching networks.

There is no substantial difference between players' behavior in global and local matching structures during the first 10 periods of pre-play. Therefore, let's consider the ABC treatments. After the addition of a new payoff-dominant strategy C, the share of its initial adopters was on average 25% higher in local networks than in the global. Consequently by the end of the 20th round, players from the global networks fluctuated back to playing the conventional risk-dominant strategy C*, while in the local matching networks the adoption of the payoff-dominant strategy C reached on average 96.9%. The Mann-Whitney two-sample ranksum test confirmed the significant difference in the rates of playing the payoff-dominant strategy C formed by the 20th round of the game in local (groups 9-12) and global networks (groups 1-4) (p=0.001). From the 21st round, in the ABC treatments in the global network, the newly introduced risk-dominant strategy C* was adopted very fast by three of four groups of the players and only by 18.75% of the subjects in the local networks.

The differences in people's coordination behavior in local and global networks were also observed in the ABC* treatments. There were observed difficulties in coordination in the pre-play rounds in all of the global ABC* sessions. After the introduction of the risk-dominant strategy C* on the 11th round, almost half of the players switched to it in the global network and only 18.5% in the local. In the next rounds for the former case the percentage of the adopters of the risk-dominant strategy grew through time till 91.9% on average between four groups while in the later fell to 12.5% after ten rounds of interaction. The difference between the adoption of a risk-dominant strategy C* on the 20th round in local (groups 13-14) and global matching networks (groups 5-8) was significant according to the Mann-Whitney two sample runksum test (p=0.001). The risk-dominant strategy C* was substituted by the payoff-dominant C strategy from the 21 round. After that, on average 67.5% of the players of the global networks switched to the efficient option and its coordination rate remained high during the next rounds. The initial adoption of the payoff-dominant strategy C in the local networks started from 56.25% on the 21 round and grew to 87.5% on average by the 30th round of the game. Here the adoption rates are quite similar, however, how it has been already explained earlier, the main reason to this might be the inability of the players to select a conventional equilibrium at the pre-play rounds and their using the last introduced strategy as a coordination device.

The experimental findings clearly showed that the coordination behavior is different in global and local interaction networks. While the local network architecture promotes coordination on efficient strategy, in the global networks players tend to select the risk-dominant strategy. Therefore, the experimental findings support the fifth hypothesis of this study.

A possible explanation to convergence to efficient equilibrium observed in local matching networks could be a subjects imitation of successful behaviors. Several theoretical and experimental studies suggest that in the local matching settings agents update their strategies following imitation rules rather than myopic best-response (Alòs-Ferrer, 2003; Alòs-Ferrer and Weidenholzer, 2006; 2008; Cui, 2014). There are two crucial factors that make successful imitation feasible in local matching that are absent in the global matching structure. First, the payoff formula in the global matching imposed a network effect that put a strict dependence between strategy's payoff and the number of its adopters. In order to be profitable, any strategy, risk-or-payoff – dominant, needed to accumulate a critical mass of adopters. While in the local matching networks, where the players were matched in pairs and possible payoffs were directly observed from the normal form game, one's earnings depended exclusively on his co-player's choice. Second, in the local matching structure a player interacts only with two immediate partners. Although players were not informed on the interaction structure, such network design together with repeated interactions made it possible for subjects to affect the choices of their neighbors.

After each interaction round, the game screen provided to the participants tables with a full feedback about the earnings of players who executed a particular game strategy. Given that, the players were able to recognize not just their immediate neighbors' success but to see also the strategy that gave the highest payoff in all of the population. All together, the above observations suggest that the convergence to the Pareto-dominant equilibrium, which was observed in the local matching treatments is caused by subjects' following the "imitate the best" rule (Schlag, 1996).

2.8 Conclusions

The experiment investigated the process of technology adoption under different conditions. Mainly I concentrated on the differences between the adoption of payoff-dominant and risk-dominant technologies in the global and in the local matching networks. The main feature of my research is that, in contrast to other studies, it considers the importance of the natural establishment of the conventional equilibrium by the players in the early rounds of the game. Moreover, I examined the process of adoption in environment with natural noise. In contrast to the studies with exogenous shocks (Corbae and Duffy, 2008), an introduction of a new option to the game creates the needed amount of noise by itself and induces players to switch.

The initial conditions were found to be a crucial factor for the adoption of a new technology. In both cases, when the newly introduced technology was represented by a risk-dominant strategy by a payoff-dominant one, the initial number of its adopters determined its further development. However, a different outcome was observed in the local matching: the players exhibited a strong tendency to switch to the payoff-dominant strategy at any occasion. This result contradicts the prognosis of Ellison's circular city model (1993) and justifies players' ability to imitate successful actions of their neighbors rather than being just myopic best-responders.

A peculiar dependence was observed when the agents failed to establish a convention in the pre-play rounds. In these cases the most probable outcome was a rapid switch to the newly added strategy independently on its risk or payoff characteristics. This behavior is associated with players' inability to converge to a common standard and the newly introduces technology serves as a focal point that facilitates coordination. Experiencing coordination problems in the beginning, players decide to remain playing the recently added strategy even when its characteristics change during the game. Nevertheless, the lock-in tended to be roughly impossible result if players managed to achieve high coordination in the pre-play rounds.

A large body of experimental literature stressed the importance of focal points in the emergence of conventions in coordination games (Mehta et al., 1994a, 1994b; Bacharach and Bernasconi, 1997; Crawford et al., 2008). Sugden (1995) considered salience according to the Schelling's (1960) definition, as an option that seems intuitively more reasonable than others and argued that it serves as an equilibrium selection mechanism in coordination games. According to him, an equilibrium, which is more salient than others, tends to be selected as a convention.

Salience serves as a good way of solving a coordination problem that players face for the first time. However if the game is played repeatedly in a population, a convention is reached rather by experimental learning[7]. In the repeated games, co-players learn to coordinate by using similarity-based rules and replicating actions that

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[7] Learning process can be well modeled by evolutionary algorithms. Learning as well as evolutionary algorithms lead to the same or similar results, which is the selection of the best performing strategy. Learning process can be well described by replicator dynamics (Brenner and Witt, 1997; Hofbauer and Sigmund, 1998; Skyrms, 2010). Instead of representing replicator dynamics as an evolution of a strategy within a population, it can be interpreted as an evolution of probability of using a particular strategy. Depending on the features of learning process, replicator dynamics can represent a psychological model of learning: if one strategy gives a larger payoff than average its usage will increase; if it yields a lower payoff it will decrease. Then the probability of choosing a certain strategy is proportional to its accumulated rewards. Therefore, it is more likely that individuals choose a strategy, which gives a greater payoff than average, which coincides with the learning by imitation model.

were successful in the past. This point was thoroughly elaborated and discussed by Skyrms (1996). He argued that a concept of salience is irrelevant in the reproduction of conventions in repeated interactions. According to him, in evolutionary coordination games a convention emerges as a matter of chance, without a need of a salient option.

The experiment presented in the current chapter has provided evidence that could support both the approaches to the emergence of conventions. In the pilot sessions, where the strategies in the pre-play were labeled A and B, all of the players in both groups selected the option A. This fully corresponds to the predictions of the salience approach, which described the top left label A to be more focal than B. During the next rounds, players continued to coordinate on the strategy A, which provided high payoff in the first coordination round and eventually became a convention. However, in the baseline sessions, after removing salience from the labels, the picture has changed. An introduction of neutral labels decreased substantially the coordination rate. Although in the next rounds most of the groups managed to coordinate and to establish a convention, now it took much more time. Therefore, the experiment supports the idea that players are more likely to select a convention, which is salient. However, it seems to happen just because they are more likely to start their development path from coordination on it. Starting a repeated coordination game in a salient point and continuation of its selection in the subsequent rounds makes it the most prominent candidate for the emergence of a convention. The salient option tends to be selected as a convention in the evolutionary games just because the initial conditions are more likely to be in the basin of attraction of that equilibrium. Receiving positive payoffs from choosing a salient strategy starting from the beginning of a game gives players no point to switch away.

Appendix A

Picture 1. The Interface of the Experiment

Graph 1. The Pilot Experiment: Average percentage of the choices in the ABC treatments: Global Matching

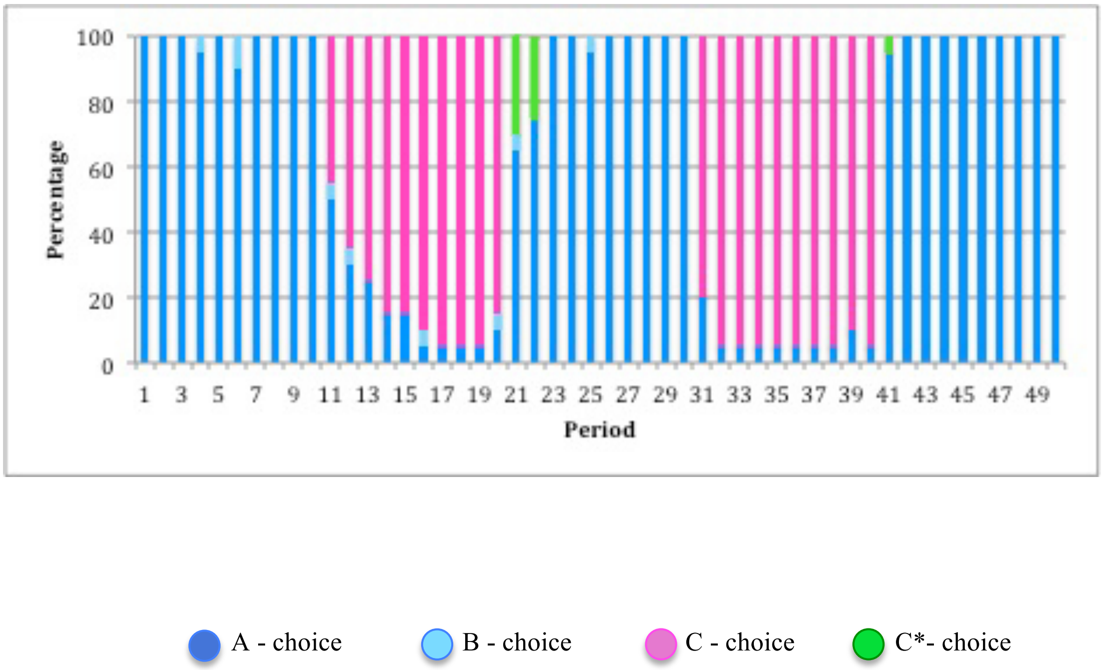


Table 1. Experimental Summary

Session	Matching Method	Treatment	Group Index	Players in a group
1	Global	ABC	1	8
	Global	ABC	2	8
2	Global	ABC	3	8
	Global	ABC	4	8
3	Global	ABC*	5	8
	Global	ABC*	6	8
4	Global	ABC*	7	10
	Global	ABC*	8	10
5	Local	ABC	9	8
	Local	ABC	10	8
6	Local	ABC	11	8
	Local	ABC	12	8
7	Local	ABC*	13	8
	Local	ABC*	14	8

Table 2. Frequency of Coordination in the Sessions 1-2 (Global Matching, ABC Treatments)

	Group 1			Group 2			Group 3			Group 4		
Period	A	B	C (C*)	A	B	C (C*)	A	B	C (C*)	A	B	C (C*)
1	87.5	12.5	0	62.5	37.5	0	62.5	37.5	0	75	25	0
2	87.5	12.5	0	75	25	0	62.5	37.5	0	62.5	37.5	0
3	75	25	0	75	25	0	75	25	0	75	25	0
4	75	25	0	50	50	0	75	25	0	100	0	0
5	87.5	12.5	0	50	50	0	75	25	0	100	0	0
6	100	0	0	50	50	0	100	0	0	75	25	0
7	75	25	0	50	50	0	100	0	0	75	25	0
8	100	0	0	37.5	62.5	0	100	0	0	100	0	0
9	100	0	0	25	75	0	100	0	0	100	0	0
10	75	25	0	62.5	37.5	0	100	0	0	87.5	12.5	0
11	25	0	75	37.5	12.5	50	50	0	50	25	0	75
12	12.5	0	87.5	12.5	12.5	75	50	0	50	50	0	50
13	0	0	100	0	12.5	87.5	50	12.5	37.5	25	0	75
14	0	0	100	12.5	12.5	75	87.5	0	12.5	37.5	0	62.5
15	0	0	100	25	12.5	62.5	100	0	0	0	0	100
16	0	12.5	87.5	50	12.5	37.5	100	0	0	25	0	75
17	12.5	12.5	75	75	12.5	12.5	100	0	0	12.5	0	87.5
18	12.5	12.5	75	62.5	37.5	0	87.5	12.5	0	37.5	0	62.5
19	25	0	75	25	37.5	37.5	100	0	0	50	0	50
20	37.5	0	62.5	37.5	25	37.5	87.5	0	12.5	75	0	25
21	12.5	25	62.5	0	37.5	62.5	100	0	0	62.5	0	37.5
22	37.5	0	62.5	25	12.5	62.5	100	0	0	75	0	25
23	25	12.5	62.5	0	12.5	87.5	100	0	0	50	12.5	37.5
24	12.5	0	87.5	0	12.5	87.5	100	0	0	25	0	75
25	0	0	100	0	0	100	100	0	0	12.5	0	87.5
26	0	12.5	87.5	25	0	75	100	0	0	0	0	100
27	0	0	100	12.5	25	62.5	100	0	0	0	0	100
28	0	0	100	0	12.5	87.5	100	0	0	0	0	100
29	0	0	100	0	0	100	100	0	0	0	0	100
30	0	0	100	0	0	100	100	0	0	12.5	0	87.5

Graph 2. Average Percentage of the Choices in the Sessions 1-2 (Global Matching, ABC Treatments)

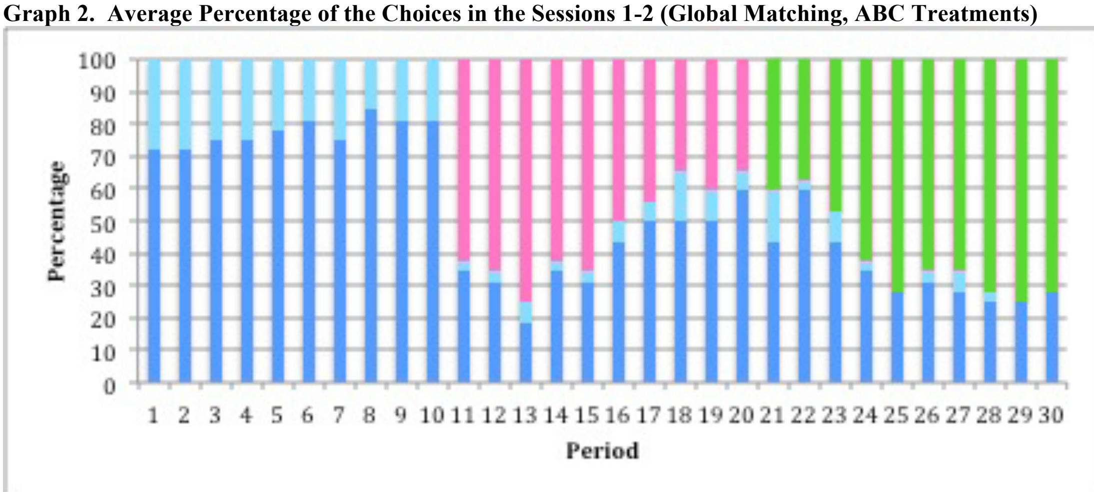


Table 3. Frequency of Coordination in the Sessions 3-4 (Global Matching, ABC* Treatments)

	Group 5			Group 6			Group 7			Group 8		
Period	A	B	C (C*)	A	B	C (C*)	A	B	C (C*)	A	B	C (C*)
1	87.5	12.5	0	87.5	12.5	0	80	20	0	90	10	0
2	62.5	37.5	0	50	50	0	50	50	0	20	80	0
3	37.5	62.5	0	50	50	0	40	60	0	10	90	0
4	12.5	87.5	0	62.5	37.5	0	10	90	0	20	80	0
5	25	75	0	100	0	0	50	50	0	60	40	0
6	50	50	0	87.5	12.5	0	70	30	0	30	70	0
7	50	50	0	50	50	0	40	60	0	30	70	0
8	37.5	62.5	0	62.5	37.5	0	50	50	0	40	60	0
9	12.5	87.5	0	75	25	0	40	60	0	50	50	0
10	25	75	0	75	25	0	40	60	0	10	90	0
11	12.5	37.5	50	37.5	0	62.5	30	30	40	30	30	40
12	0	37.5	62.5	25	12.5	62.5	20	30	50	20	30	50
13	0	25	75	37.5	0	62.5	0	20	80	0	0	100
14	0	12.5	87.5	25	0	75	0	10	90	0	0	100
15	0	12.5	87.5	0	0	100	0	10	90	0	0	100
16	0	12.5	87.5	0	0	100	0	0	100	0	0	100
17	0	0	100	0	0	100	10	0	90	10	0	90
18	0	0	100	25	12.5	62.5	0	20	80	0	0	100
19	0	0	100	25	12.5	62.5	0	20	80	0	0	100
20	0	12.5	87.5	0	0	100	10	0	90	10	0	90
21	25	0	75	0	25	75	20	40	40	10	10	80
22	37.5	0	62.5	12.5	0	87.5	40	30	30	0	10	90
23	37.5	0	62.5	0	25	75	30	30	40	0	10	90
24	37.5	0	62.5	0	25	75	20	30	50	10	0	90
25	25	0	75	12.5	0	87.5	0	20	80	0	10	90
26	0	0	100	25	0	75	10	0	90	10	0	90
27	0	0	100	12.5	12.5	75	10	0	90	10	10	80
28	0	0	100	0	12.5	87.5	0	0	100	10	10	80
29	0	12.5	87.5	12.5	12.5	75	0	0	100	10	10	80
30	0	12.5	87.5	12.5	12.5	75	0	0	100	0	30	70

Graph 3. Average Percentage of the Choices in the Sessions 3-4 (Global Matching, ABC* Treatments)

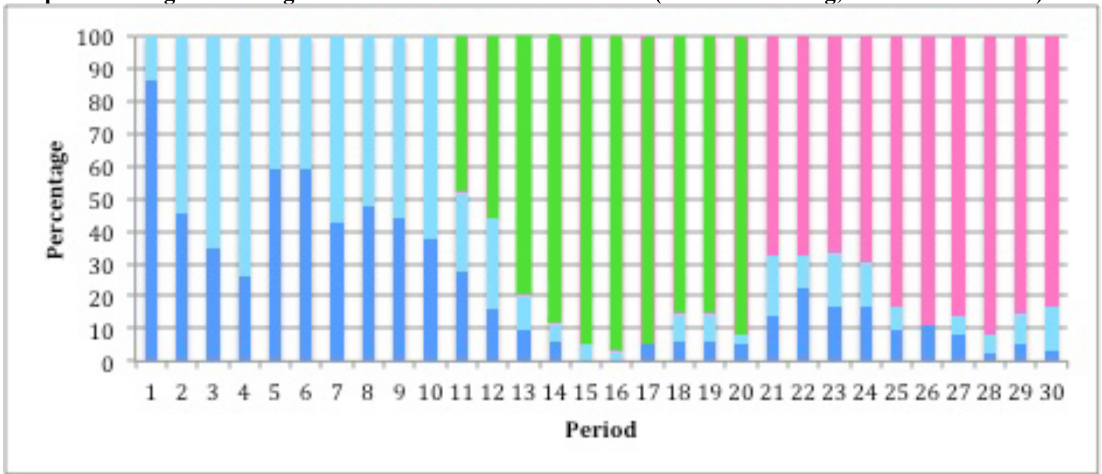


Table 4. Frequency of Coordination in the Sessions 5-6 (Local Matching, ABC Treatments)

	Group 9			Group 10			Group 11			Group 12		
Period	A	B	C (C*)	A	B	C (C*)	A	B	C (C*)	A	B	C (C*)
1	75	25	0	75	25	0	75	25	0	87.5	12.5	0
2	62.5	37.5	0	62.5	37.5	0	62.5	37.5	0	62.5	37.5	0
3	62.5	37.5	0	62.5	37.5	0	75	25	0	62.5	37.5	0
4	50	50	0	50	50	0	75	25	0	62.5	37.5	0
5	75	25	0	75	25	0	75	25	0	87.5	12.5	0
6	62.5	37.5	0	62.5	37.5	0	75	25	0	87.5	12.5	0
7	87.5	12.5	0	87.5	12.5	0	50	50	0	75	25	0
8	87.5	12.5	0	87.5	12.5	0	62.5	37.5	0	87.5	12.5	0
9	87.5	12.5	0	87.5	12.5	0	75	25	0	100	0	0
10	100	0	0	100	0	0	75	25	0	75	25	0
11	25	0	75	25	0	75	12.5	12.5	75	0	0	100
12	12.5	12.5	75	12.5	12.5	75	0	12.5	87.5	0	0	100
13	12.5	0	87.5	12.5	0	87.5	12.5	0	87.5	0	12.5	87.5
14	0	0	100	0	0	100	0	12.5	87.5	0	12.5	87.5
15	0	0	100	0	0	100	0	12.5	87.5	12.5	0	87.5
16	12.5	0	87.5	12.5	0	87.5	0	12.5	87.5	25	0	75
17	0	0	100	0	0	100	12.5	0	87.5	0	0	100
18	12.5	0	87.5	12.5	0	87.5	0	0	100	25	12.5	62.5
19	12.5	0	87.5	12.5	0	87.5	0	0	100	0	25	75
20	0	0	100	0	0	100	0	0	100	12.5	0	87.5
21	50	12.5	37.5	50	12.5	37.5	37.5	12.5	50	50	25	25
22	62.5	12.5	25	62.5	12.5	25	12.5	25	62.5	75	12.5	12.5
23	62.5	25	12.5	62.5	25	12.5	12.5	25	62.5	50	37.5	12.5
24	75	12.5	12.5	75	12.5	12.5	0	37.5	62.5	50	25	25
25	75	12.5	12.5	75	12.5	12.5	12.5	37.5	50	75	12.5	12.5
26	75	0	25	75	0	25	0	50	50	87.5	0	12.5
27	75	0	25	75	0	25	0	37.5	62.5	50	37.5	12.5
28	75	0	25	75	0	25	0	37.5	62.5	62.5	37.5	0
29	75	12.5	12.5	75	12.5	12.5	0	50	50	75	0	25
30	75	12.5	12.5	75	12.5	12.5	0	50	50	87.5	0	12.5

Graph 4. Average Percentage of the Choices in the Sessions 5-6 (Local Matching, ABC Treatments)

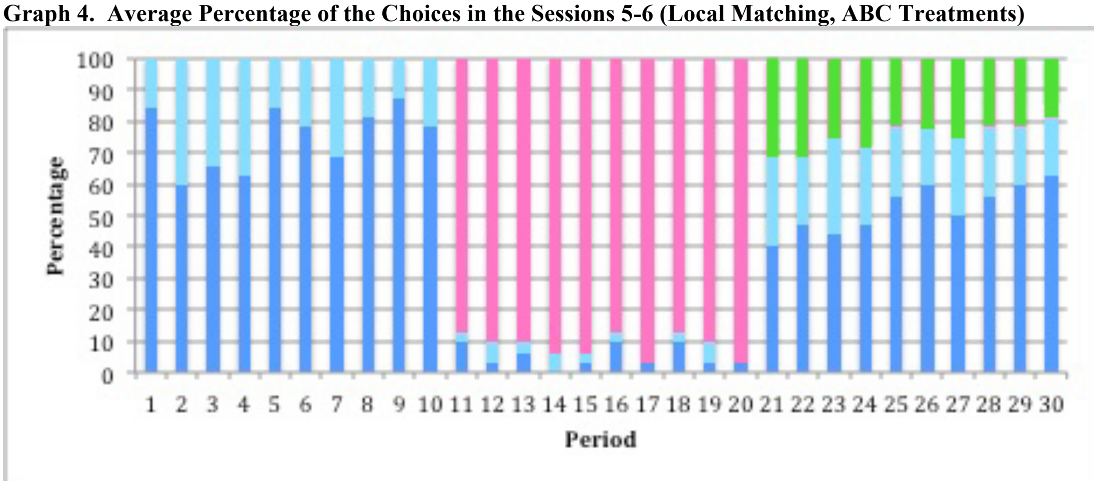
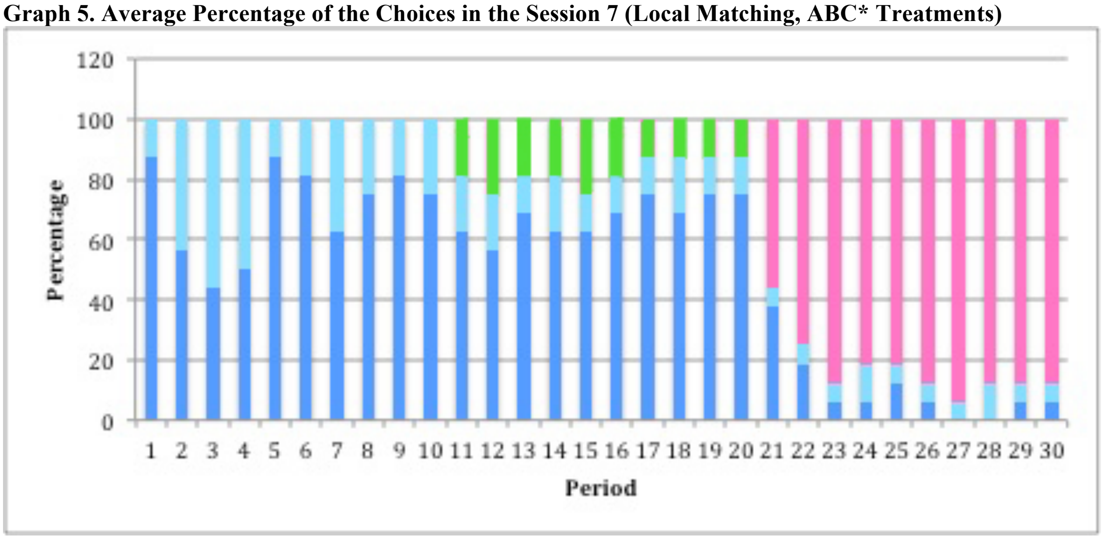


Table 5. Frequency of Coordination in the Session 7 (Local Matching, ABC* Treatments)

	Group 13			Group 14		
Period	A	B	C (C*)	A	B	C (C*)
1	87.5	12.5	0	87.5	12.5	0
2	50	50	0	62.5	37.5	0
3	12.5	87.5	0	75	25	0
4	25	75	0	75	25	0
5	75	25	0	100	0	0
6	62.5	37.5	0	100	0	0
7	37.5	62.5	0	87.5	12.5	0
8	50	50	0	100	0	0
9	62.5	37.5	0	100	0	0
10	50	50	0	100	0	0
11	37.5	37.5	25	87.5	0	12.5
12	25	37.5	37.5	87.5	0	12.5
13	37.5	25	37.5	100	0	0
14	25	37.5	37.5	100	0	0
15	25	25	50	100	0	0
16	37.5	25	37.5	100	0	0
17	50	25	25	100	0	0
18	37.5	37.5	25	100	0	0
19	50	25	25	100	0	0
20	50	25	25	100	0	0
21	62.5	12.5	25	12.5	0	87.5
22	37.5	12.5	50	0	0	100
23	12.5	12.5	75	0	0	100
24	12.5	25	62.5	0	0	100
25	25	12.5	62.5	0	0	100
26	12.5	12.5	75	0	0	100
27	0	12.5	87.5	0	0	100
28	0	25	75	0	0	100
29	12.5	12.5	75	0	0	100
30	12.5	12.5	75	0	0	100

Graph 5. Average Percentage of the Choices in the Session 7 (Local Matching, ABC* Treatments)



3. The Power of Dominated Strategies

3.1 Introduction

Numerous methods have been developed in order to determine which of several equilibria will be selected in games with multiple equilibria. In general, all these concepts are reduced to the recognition that the selected equilibrium must be a strict Nash equilibrium. The works of evolutionary economists such as Young (1993), KMR (1993), Ellison (1993) provided more strict refinement to the equilibrium selection in the presence of multiple Nash equilibria. The basic idea of their approach is a consideration of the transitions probabilities between the basins of attraction of the equilibria of a game. Since the basin of attraction of the risk-dominant (or ½ dominant) equilibrium is larger than the basin of attraction of the payoff-dominant equilibrium it requires less mutations for the population to shift from one equilibrium to another. Therefore, the risk-dominant equilibrium is more likely to be selected in the long-run as the unique stochastically stable equilibrium.

Classical game theory assumes that dominated strategies should play no role in equilibrium selection. When player's rationality is common knowledge, iteratively dominated strategies will be deleted from the game before any other refinement is applied. Several studies suggest that eliminating dominated strategies does affect the process of equilibrium selection. This has been observed experimentally, starting with Cooper et al. (1990), and theoretically in the context of noisy evolutionary models that showed how a dominated strategy may influence players' choices (Maruta, 1997; Ellison, 2000). Maruta (1997) and Ellison (2000) used the radius-coradius method of equilibrium selection and were the first to consider how the addition of a dominated strategy changes the sizes of the basins of attraction of the incumbent equilibria. More recently, Basov (2004) and Kim and Wong (2010) adopted this approach and showed that the long-run stochastically stable equilibrium is highly sensitive to the addition and elimination of dominated strategies to the original game. The authors demonstrated that the dominated strategies may support the selection any of the game's strict equilibria through changing the sizes of the best-respond regions of equilibria of a game in a way that a very small fraction of mutants is needed for a shift. As a result, by adding suitably chosen dominated strategies to a game, any strict equilibrium of that game can be made stochastically stable.

In this work I perform an experiment that challenges the results of Kim and Wong (2010). I run a coordination game with two equilibria one risk-dominant the other payoff-dominant. I run a few rounds in which players are allowed to converge to one of the equilibria of the game. At this point I add a third strategy, which is strictly dominated by both original strategies. The properties of the dominated strategy depends on the equilibrium selected at the pre-play stage: if the players have converged to the risk-dominant equilibrium the dominated strategy expands the basin of attraction of the payoff-dominant equilibrium; if the payoff-dominant equilibrium has been pre-selected, the added dominated strategy expands the basin of attraction of the risk-dominant equilibrium. In both cases, the introduction of the dominated strategies reduces the number of mutants required for the transition from one equilibrium to the other. Kim and Wong model (2010) would then predict the same ease of transition from the risk-dominant to the payoff-dominant equilibrium and *vice versa*. The addition of a dominated strategy after the establishment of the conventional equilibrium during the pre-play rounds, allows to capture the changes in the behavior of the players better than just including it from the very first round.

The results of my experiment don’t lend support to this hypothesis: in the majority of the cases the players converged to the risk-dominant equilibrium and the introduction of the dominated strategy failed to induce a switch towards the payoff-dominant equilibrium. In those cases in which the players converged to the payoff-dominant equilibrium, the introduction of a dominated strategy that expands the basin of attraction of the risk-dominant equilibrium was sufficient to provoke a transition towards that equilibrium.

The results of my experiment confirm the robustness of the KMR (1933) model to the presence of the dominated strategies: the population tended to select the risk-dominant equilibrium in both games, with and without a dominated strategy. They also go in line with the research by Weidenholzer (2010, 2012) who considered the introduction of the dominated strategies to the circular city model. In general, the stochastic models were observed to provide an accurate prognosis, which is the risk-dominant outcome.

3.2 Literature review

In this section I discuss the works that investigate the process of equilibrium selection in coordination games with strictly dominated strategies. I start with the early classical literature on the topic of equilibrium selection and proceed to more recent experimental and theoretical works that analyze how the presence of strictly dominated strategies affects equilibrium selection in games with multiple equilibria.

A common technique in finding Nash Equilibria in strategic games is the iterated elimination of dominated strategies (see Fudenberg and Tirole, 1993; Gintis, 2000). According to it, all strictly dominated strategies for each player should be eliminated from a normal form game. A strategy is strictly dominated if there exists another strategy (possibly mixed), which gives a better payoff independently from the actions of other players. Rational players will never use strictly dominated strategies. When rationality is common knowledge, then strictly dominated strategies will be eliminated iteratively. After the first round of elimination, a deletion of strictly dominated strategies continues in a smaller normal form game until no more strictly dominated strategies remain for neither player. Since strictly dominated strategies cannot be part of Nash Equilibrium, the order in which they are eliminated is irrelevant. Elimination of weakly dominated is more controversial as such strategies may be part of Nash equilibria, and hence removing them also removes equilibria of the game. Also, the Nash equilibria that survive the process of iterate elimination depends upon the order in which the elimination takes place.

While classical game theory postulates that strictly dominated strategies are never chosen by rational players, experimental studies show that dominated strategies are frequently played. For example, cooperation is frequently observed in one-shot prisoner's dilemma games (Axelrod, Riolo and Cohen, 2002; Nowak et al. 2004; Ethan, 2013; Capraro, 2013). However, such drastic deviation from economic rationality seems to be not robust to learning, since the experimental evidence shows that cooperation declines over time, eventually becoming irrelevant (Van Huyck et al.1990; Dal Bó and Fréchette, 2013).

Although dominated strategies can never constitute an equilibrium in a game, they may influence equilibrium selection in games with multiple equilibria just by their presence. Cooper et al. (1990) conducted an experiment where they showed how strictly dominated strategies affect the choices of individuals. The authors considered a 3x3 normal form game with an efficient non-equilibrium outcome constituted by strictly dominated strategies. They demonstrated that despite participants almost never chose the dominated strategy, by manipulating the payoffs it yields would change the result of the game. In particular, correspondence of the highest payoff of dominated strategy to a particular strategy combination determined which of two Pareto-ranked Nash equilibria was selected. Probably, one of the reasons for this was the salience of high payoff (albeit dominated) located in the same row, which pointed which strategy to choose. Cooper et al. (1990) demonstrated the focal power of dominated strategies, which are never played in the game, however the analysis of the dynamics of convergence affected by their introduction is lacking. However, the paper by Cooper et al. (1990) did not consider the difference between risk-dominance and payoff-dominance and did not explicitly model the dynamic process of equilibrium selection. Moreover, the authors included a cooperative non-equilibrium state that in several treatments gave a Pareto-dominant payoff relatively to both equilibria payoffs of the game. This partially modified the game into a prisoners' dilemma case, which may have created biases in individualistic behavior. The reason for this is that a prisoners' dilemma game illustrates a conflict between individual and group rationality. Cooperation here is the worst strategy to choose, and therefore players perceive their interests against of the interests of their mates. Moreover, since *cooperation* in a prisoners' dilemma not an equilibrium state this strategy could not survive in a long-run. In contrast, in a stag hunt game a cooperative strategy is represented by an equilibrium state, which is also more profitable for an individual than other strategy. Although the payoff of an individual in in the stag hunt game depends in the action of his co-players, the conflict is between the risk and return rather than between individual and group interests. Therefore, a player does not perceive a choice of a cooperative strategy as a contribution against his own interests.

Bosch-Domènech and Vriend (2008) explored the role of non-equilibrium focal points on the emergence of coordination in games with multiple equal Nash equilibria. In their experiment, focal points were represented by dominated strategies, which were also Pareto-dominated by all existing equilibria. Nevertheless, those dominated strategies attracted players' attention and pointed out which strategy to choose. The authors noticed that subjects coordinated on a small subset of Nash Equilibria, which was located closely to the focal strategies. A similar spirit had an experimental study by Huber et al. (1982). They performed an experiment whose results are today frequently applied in marketing. The authors explored the power of asymmetrically dominated products on consumer decisions. Although choosing such products was never the best-reply, it became hugely favored in a market. Therefore, a dominated alternative may serve as an instrument that reduces uncertainty in comparing options across many dimensions or decisions of other participants of a market.

The idea of studying the relevance of dominated strategies in equilibrium selection is relatively new in the theoretical literature. Several studies pointed out that the evolutionary dynamic process of equilibrium selection is highly influenced by dominated strategies. Precisely, these works focused on the evolutionary dynamic games with multiple Nash equilibria. They provided a way to influence on equilibrium selection in the long-run through adding and removing dominated strategies to a game. Maruta (1997) and Ellison (2000) first provided examples of how the addition of dominated strategies changes the sizes of the basins of attraction of equilibria in a game thus changing the stochastically stable equilibrium. Later, Myatt and Wallace (2003) proposed a multinomial probit model as an elaboration the KMR (1993) work on stochastic equilibrium selection. The main peculiarity of their approach was a transformation of noise from KMR model into trembles, which were added directly to the payoffs. They introduced a third dominated strategy to the 2x2 game with two equilibria: payoff and risk-dominant. The introduced strategy was strictly dominated by the risk-dominant strategy and weakly dominated by the payoff-dominant strategy. Such an addition did not change the ½ dominance of the existing equilibria. One deviation from the risk-dominant equilibrium in favor of newly introduced strategy was enough for a transition to a payoff-dominant equilibrium. A payoff-dominant equilibrium in this case became a best-response to the newly introduced dominated strategy. In this way, Myatt and Wallace (2003) provided an additional method, which enables transition to a more efficient state, and demonstrated how the introduction of a strictly dominated strategy affects the long-run distribution.

Basov (2004) continued research in the field of equilibrium selection and provided examples, which demonstrated that dominated strategies may not only promote transition from the risk-dominant to the payoff dominant equilibrium but also the other way around. Using Ellison's (2000) radius-coradius method, he demonstrated that the long-run equilibrium is sensitive to the payoffs of the dominated strategy. Further, Kim and Wong (2009) showed that the dominated strategies under the assumption of best-response learning may change the long-run outcome of the game. Precisely, they affect the sizes of the basins of attraction of Nash equilibria in a game, in a way that adding a dominated strategy may support any Nash equilibria. The results of this work coincide with the previous findings, showing that the long-run predictions of the stochastic models are sensitive to the introduction of apparently irrelevant strategies. Besides the demonstration that dominated strategies change the basin of attraction of any equilibrium, they proved that any convex combination of strict Nash equilibria "can be realized as the long-run distribution by appropriately adding strictly dominated strategies" (p. 243, Kim and Wong, 2009).

Weidenholzer has recently revisited the literature on this topic and concluded that the only stochastically stable outcome in the long-run is playing the ½-dominant strategy. (Weidenholzer, 2010, 2012) In his more recent work, Weidenholzer (2012) provided theoretical justifications that the circular city model is robust to any addition of dominated strategy if interaction is sufficiently local. The author based his arguments on the nature of interactions between the agents around the circle. He assumed that if one player mutates to a dominated strategy it would lead his neighbors to best-respond to it switching to the payoff-dominant strategy supported by dominated one. Later players will have to best-respond to the to this choice and this would make them adjust again their strategies in favor of ½-dominant one. Having stated that such an adjustment spreads out contagiously, author, however, agreed that in 3x3 class games local and global matching protocols might lead to different results. Weidenholzer (2012) attracts the attention to the distinctions between the long-run predictions for global and local interaction protocols, especially for games with multiple strategies. Given the high contagious nature the circular city model, the author points out that its results serve as a preliminary background to study other matching structures but not as a general prediction for coordination games.

Sandholm and Hofbauer (2011) considered the case in the absence of convergence and showed that in deterministic evolutionary dynamics a dominated strategy may be played by a significant numbers of subjects. They determined four conditions under which the elimination of strictly dominated strategy leads to consequences in equilibrium convergence. The conditions require continuity – continuous dynamics change as a function of payoff and state; positive correlation between strategies' payoffs and growth rates away from equilibrium; Nash-stationarity – states that are not Nash equilibria should not be rest-points of the dynamics, and a positive growth rate of an unused strategy which is a best-response. Adhering to these conditions the authors modeled a game that explicitly showed how a strictly dominated strategy persists during the game development.

3.3 Influence of the Dominated Strategies on Equilibrium Selection. Theoretical considerations

In the present section, I describe the mechanisms elaborated by Kim and Wong (2009) and Basov (2004) that questioned the robustness of the predictions of KMR model. The essence of their method is based on an apparently innocent extension of the game through the introduction of a dominated strategy. Such introduction, depending on the properties of a dominated strategy, may support the long-run selection of any equilibrium in the game through changes in the best-respond regions. The matrix in Table 10, adapted from Kim and Wong (2010), illustrates this point.

Suppose, there is a 2x2 game with two Nash equilibria: one payoff-dominant *(A,A)* and another the risk-dominant *(B,B)*. In random perturbation models, the equilibrium with the largest basin of attraction will be eventually selected in the long-run as the unique stochastically stable outcome. (Figure 5).

	A	B
A	8, 8	0, 4
B	4, 0	6, 6

Table 10. 2x2 Coordination Game

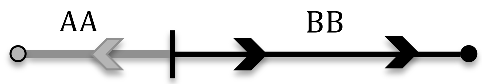


Figure 5. Basins of Attraction of the Equilibria AA and BB in 2x2 game

Table 11 represents the same game, now embedded in a larger 3x3 game in which players can also choose a dominated strategy C (X>0). Since C is strictly dominated, this does not alter the existing Nash equilibria of the game. However, the sizes of the basins of attraction, and therefore the long-run distribution now change dramatically. In Figure 6, the white triangle is the basin of attraction of the *(B, B)* equilibrium and the grey triangle is the basin of attraction of the *(A,A)* equilibrium.

	A	B	C
A	8, 8	0, 4	-X, -3X
B	4, 0	6, 6	-2X, -3X
C	-3X, -X	-3X, -2X	-3X, -3X

Table 11. 3x3 Game with a Dominated Strategy

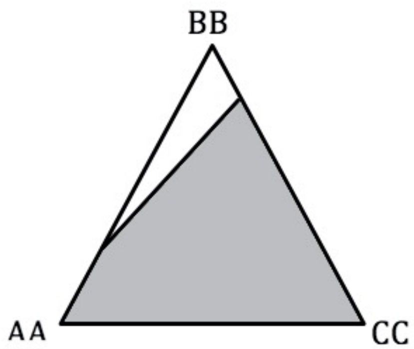


Figure 6. Basins of Attraction of the 3x3 Game with a Dominated Strategy C

The introduction of the dominated strategy C substantially changes the best-respond regions in the game. Since C is strictly dominated, there is no area in the triangle in which it is a best-response. However, its presence facilitates escaping from the basin of attraction of the equilibrium *(B,B)* and supports adoption of the strategy A. To see this, consider that for A to become a best response, it takes only a small number of agents to switch to strategy C. If the value of X is sufficiently large, the fraction of agents who need to switch to C to trigger a transition from *(B,B)* to *(A,A)* can be made arbitrarily small. These results are purely theoretical. In this work I test them experimentally.

3.4 Hypotheses and Experimental Design

For the current experiment participants were organized in groups of 10 (8 in few cases when participants did not show up for the experiment). They played a coordination game for 30 rounds. I adopted the KMR matching method where each player is playing against the population as a whole. For the first pre-play rounds of the game players had to choose between 2 strategies labeled neutrally as $ and @ in order to avoid label salience (we shall refer to them as strategies A and B further in text for purposes of exposition). These strategies form a game with Pareto-ranked equilibria, where equilibrium *(A,A)* is risk-dominant and equilibrium *(B,B)* is payoff-dominant. As soon as the population reached a convention, i.e. converged to one of equilibria and remained there for several rounds, a third strategy was introduced.[8]

The characteristics of the newly introduced dominated strategy depend on which equilibrium had become a convention in the initial rounds. If the population converged to the risk-dominant equilibrium *(A,A),* the newly introduced strategy C (labeled # for the players) would expand the basin of attraction of the equilibrium *(B,B).* If, in contrast, after the first rounds the payoff-dominant strategy B became the

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[8] For the periods from 1 to 8 the required rate of convergence had to be more than 90%. For the last three rounds and for the later rounds the assumption was looser: a strategy was said to be adopted if in the last two rounds it was chosen by more than 80% of the players. After that, the players choose between three strategies until the end of the game.

dominant choice, the new strategy Z (labeled % for the players), would enlarge the basin of attraction of the equilibrium *(A,A)* (see Tables 12, 13).

Such experimental design has two purposes. First is that before running the experiment it is impossible to predict whether the participants would converge either to the risk-dominant or to the Pareto-dominant equilibrium. Therefore, in order to ascertain results, the design includes two versions of the game scenario. Second, it is unlikely that in all the experimental sessions the outcome of the first pre-play rounds would be the same. It was expected that the convergence might be different from session to session. Therefore, such experimental design provides us observations for both cases: when the risk-dominant strategy was selected by majority and when the payoff-dominant was selected by most of the population.

	C	A	B
C	0, 0	0, 45	0, 135
A	45, 0	**30, 30**	**30, 0**
B	135,0	**0, 30**	**40, 40**

Table 12. Game CAB. Dominated Strategy C in Case Convergence to the Risk-Dominant Equilibrium

	A	B	Z
A	**30, 30**	**30, 0**	135,0
B	**0, 30**	**40,40**	45, 0
Z	0, 135	0, 45	0, 0

Table 13. Game ABZ. Dominated Strategy Z in Case of Convergence to the Payoff-Dominant Equilibrium

In both cases strategies C and Z are strictly dominated by both strategies A and B. However, strategies C and Z have substantial differences between each other. While strategy C supports the payoff-dominant equilibrium *(B,B)*, strategy Z, in contrast, supports the risk-dominant equilibrium *(A,A)*. The values for each dominated strategy are calculated in a way that provides precise changes in the best-response regions. In the initial 2x2 game, the sizes of the basins of attraction were

0.25 and 0.75 for payoff-dominant and risk-dominant equilibria respectively. The radius of the risk-dominant equilibrium (*A,A)* was 0.75 and its coradius was 0.25. It meant that in order to make the adoption of the equilibrium (*A,A)* more profitable relatively to the adoption of equilibrium *(B,B)* for all the subsequent adopters of (*A,A),* 0.25 of population was needed. And otherwise, the adoption of the equilibrium *(B,B)* would become more profitable relatively to *(A,A)* if more than 0.75 of population has adopted it.

Figure 7 illustrates this point. It represents the basins of attraction of the game in Table 12. Here, the grey area is the basin of attraction of the equilibrium *(B,B).* After the introduction of the dominated strategy C, to move from the equilibrium *(A,A)* to the basin of attraction of equilibrium *(B,B)* takes only 0.25 of the population to mutate to C, as to make B a best response. Now for a profitable adoption of equilibrium *(B,B)* would be enough just 0.25 of population to mutate towards equilibrium *(C,C)*. In this game, moving from *(A,A*) to *(B,B)* is just as easy, in terms of mutations, as moving in the opposite direction.

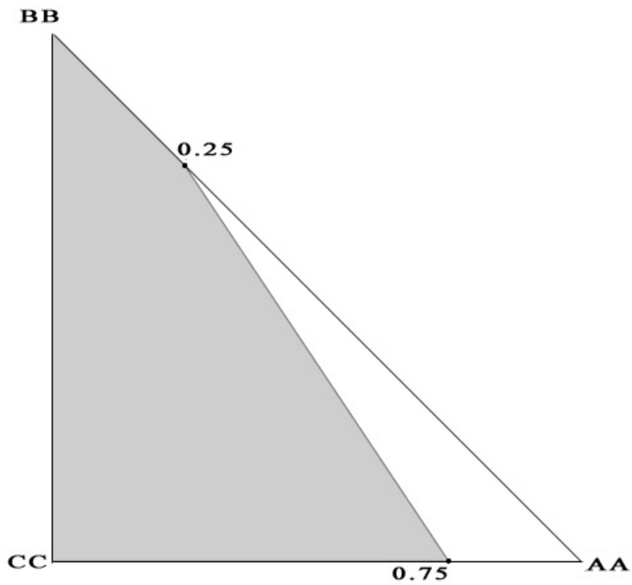


Figure 7. Game CAB. Changes in the Basin of Attraction After the Introduction of the Dominated Strategy C.

On the other hand, in the case when in a 2x2 game the population has converged to the efficient *(B,B)* equilibrium, the introduction of dominated strategy Z changes the picture even more dramatically. Convergence to the payoff-dominant equilibrium, unless the initial conditions were in favor of it, is unlikely since the basin of attraction of efficient equilibrium *(B,B)* was only 0.25. Therefore, in this case the introduction of a dominated strategy Z aims to support risk-dominant equilibrium *(A,A)* by means of enlarging its basin of attraction and reducing even more the basin of attraction of the equilibrium *(B,B)*. This enlargement is illustrated on the Figure 8 where the basin of attraction of the equilibrium *(A,A)* is white and the basin of attraction of the equilibrium *(B,B)* is grey. The introduction of the dominated strategy Z, presented in the table 13 reduces the number of mutations to get from *(B,B)* to *(A,A)* from 0.25 to 0.1. Notice that for example, in a population with 10 individuals, in order to shift from *(B,B)* to *(A,A)* only one mutation to Z is needed, instead of three directly towards equilibrium *(A,A)*. In this way, according to stochastic models, the population should finally converge to the risk-dominant equilibrium *(A,A)*.

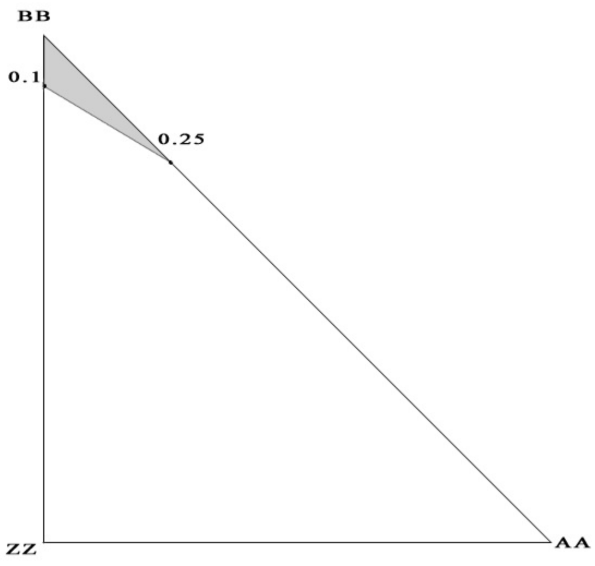


Figure 8. Game ABZ. Changes in the basin of attraction after the introduction of the dominated strategy Z.

The introduction of a dominated strategy is executed during the game after the establishment of a conventional equilibrium since it allows to trace better the changes in the behavior of individuals than it would be visible in case of its presence in the game since the first round. Moreover, such design allows to study the dynamics of players' behavior and test whether the presence of the dominated strategy provokes transitions from one equilibrium to another. As it is visible from the table, strategies C and Z are added to the game in different locations. It is done in order to reduce the visual focalily of the equilibrium we wish to support induced by high numbers, which are located near it in the table. The highest payoffs from the dominated strategy were intentionally located in a table away from the equilibrium, which they are expected to support. In this way they should neither attract the attention of the players nor point visually which equilibrium to select.

According to the predictions of classical game theory, since strategies C and Z are dominated and rational players should not consider them. The introduction of a dominated technology should not cause mutations and change the performance of the players. However, recent theoretical studies suggest that the presence of a dominated strategy might be an important factor in equilibrium selection in the long-run and is able to change the outcome of the games. Therefore, the hypotheses which the present experiment tests concern the ability of a dominated strategy to affect the game and lead to a transition from a ½-dominant to a payoff-dominant equilibrium or otherwise.

Hypothesis 1: Adding a dominated strategy changes the outcome of the game from the risk-dominant to payoff dominant equilibrium.

Hypothesis 2: A dominated strategy changes the outcome of the game from the Pareto-efficient to risk-dominant.

3.5 Results

The experiment has been conducted in the experimental laboratory of the university of Trento between September and October 2014. In total 76 students from the University of Trento participated in four sessions of the experiment. The subjects were recruited through emails, which offered to take part in an economic experiment. Each experimental session lasted about 50 minutes including reading aloud the instructions and answering the questions regarding them. The average payment earned by a participant was 8.2 euros including a show-up fee of 3 euros. The software for the experiment was written in z-Tree developed by Fischbacher (2007). The experiment consisted of four sessions, in each of them participants were randomly assigned into two groups of equal size. The session 1 consisted of two groups of eight players while in the sessions 2, 3 and 4 consisted of two groups of 10 players each[9]. Therefore, the experiment involved 8 independent treatment groups and thus provided 8 independent observations (see table in the Appendix B for experimental data).

A dominated strategy was introduced after the players in a group converged to one of equilibria of the game: risk-dominant or payoff-dominant. During the experiment, one of two strategies has become conventional on average on the 11th round. A convention has never been established earlier than on the 10th round in neither group. After the convention has been selected, the dominated strategy of correspondent characteristics was added to the game.

The experimental data showed that in the majority of the cases the players have converged to the risk-dominant equilibrium during the pre-play rounds. In 6 out of 8 cases the risk-dominant equilibrium *(A,A)* was selected by the subjects while the

[9] The fewer number of players in the first session was due to students' low turnout to the experiment that day.

convergence to the payoff-dominant equilibrium *(B,B)* was observed only in two cases. Therefore, the experiment involves 6 cases of subjects playing the Game CAB, where the dominated strategy C expands the basin of attraction of the payoff-dominant equilibrium; and only 2 cases of playing the Game ABZ, where the dominated strategy expands the basin of attraction of the risk-dominant equilibrium. In all of the groups, the introduction of a dominated strategy, whether Z or C, had an effect. In both cases, after the introduction of a dominated strategy, the percentage of playing the strategy supported by the dominated one increased on average on 32.2%. However, in most of the cases this effect disappeared after 3-4 playing rounds.

First, let's consider the game CAB, that is the case in which the basin of attraction of the payoff-dominant equilibrium was expanded. The properties of the dominated strategy "C" adjusted the game AB in a way that with its presence a transition from the basin of attraction of the risk-dominant equilibrium *(A,A)* to the basin of attraction of the payoff-dominant equilibrium *(B,B)* theoretically required a switch of ¼ of the group towards strategy C instead of ¾ mutants towards B. In all of the cases, the share of the initial adopters of the payoff-dominant strategy B after the introduction of the strategy C has increased on 25% as minimum to 62.5% as maximum. The coordination on the equilibrium *(B,B)* has reached on average 50% among 6 groups. However, in the next rounds in 5 out of 6 groups the rate of playing the payoff-dominant strategy B tended to decrease. Only one group has finally converged to the efficient outcome, while in all other cases the players have turned back to the original equilibrium constituted at the pre-play, which is risk-dominant. Although the share of mutants has crossed the threshold of ¼ of the population, it did not cause a finalized adoption of the payoff-dominant equilibrium *(B,B).* The reason for this is that this share is the share of mutants from equilibrium *(A,A)* towards the strategy B directly, not the mutants who switched from *(A,A)* to the strategy C. Entering the basin of attraction of equilibrium *(B,B)* and leaving the basin of attraction of *(A,A)* would only be possible if ¼ of the players switched to the dominated strategy C itself. Since the direct mutation from *(A,A)* to *(B,B)* required ¾ of the group to mutate to B, the accumulated percentage was not enough to enter the basin of attraction of the equilibrium *(B,B)* directly from the basin of attraction of equilibrium *(A,A)*.

Therefore, the first hypothesis that has been tested is rejected. The introduction of a dominated strategy that enlarges the basin of attraction of the Pareto efficient equilibrium had only a temporary effect: after a few fluctuations towards it the players have returned to the original equilibrium. It is possible to assume that a high initial rate of coordination on a payoff-dominant strategy was rather achieved by the focal effect or a novelty effect created by the addition of a new strategy. Independently of the reason that caused players to change their choices, the transition towards the basin of attraction of the payoff-dominant equilibrium occurred only in 2 cases out of 6, and was not caused by mutations to the dominated strategy C (see graphs 6-11 in the Appendix B). Despite the theoretical assumptions that the presence of the dominated strategy C facilitates the adoption of the payoff-dominant equilibrium, one single group that has finally converged to it did not recourse to playing the dominated strategy. However, it is possible to assume that such result is due players' rational expectations concerning the choices of their co-players. Probably, the players realized that nobody would play the dominated strategy C and therefore did not play the best-response to it. In this case, the rejection of the first hypothesis is caused by the common knowledge of rationality, which was inherent to the experimental subjects, rather than inconsistency of the theoretical predictions.

Now, let's consider the game ABZ, which results are more ambiguous. Convergence to the risk-dominant equilibrium at the pre-play was the prevalent result of the experiment, and therefore there is very few data on the case when the established equilibrium was payoff-dominant. The limited number of observations makes it difficult to draw conclusions about the tested hypotheses considering only two cases with opposite outcomes (see graphs 12-13 in the Appendix B). Due to this reason the analysis below is merely descriptive.

In both cases, when the players converged to the payoff-dominant equilibrium, the presence of a newly introduced dominated strategy provoked switches. The presence of the dominated strategy Z enabled a switch from the basin of attraction of the payoff-dominant equilibrium *(B,B)* to the basin of attraction of the risk-dominant equilibrium *(A,A)* just in 1 mutation. The players indeed changed their strategies after the introduction of the strategy Z: on average 35% of the population switched to the risk-dominant strategy A instead of the established best-response choice, which is playing payoff-dominant strategy B. Therefore, the introduction of the dominated strategy Z caused a transition to the basin of attraction of the risk-dominant equilibrium *(A,A)*. During the next 10 rounds in both cases the rate of playing the risk-dominant strategy tended to increase. However, by the end of the game while one of two groups finally adopted the risk-dominant equilibrium *(A,A)*, the players of the other one slowly fluctuated back to playing the original payoff-dominant equilibrium. A possible cause of such opposite results might be a diverse number of choices of the dominated strategy Z in two groups. The group that had finally converged to the risk-dominant equilibrium had the largest number of the simultaneous mistakes, which is playing the dominated strategy Z, which significantly increased the payoff for playing the risk-dominant strategy A. Given these two different outcomes; I can neither reject nor confirm the second hypothesis. However, it seems easier to support a switch towards the risk-dominant equilibrium than towards the payoff-dominant one. The most plausible answer to the question if the dominated strategy may affect the equilibrium selection would probably depend on the extent of players' rationality, which makes them select the dominated strategy. Its selection provides real changes in the payoffs of the players that play the strategy supported by it. Without these mistakes players do not realize possible changes in their payoffs and especially in the sizes of the basins of attraction; and after few attempts to play a strategy supported by a dominated one they return to the previously selected equilibrium.

3.6 Conclusions

The results of the present experiment showed a consistent tendency of individuals to select a risk-dominant outcome. A dominated strategy, introduced to the game after the selection of a conventional equilibrium reduced the number of mutants necessary for the transitions from one basin of attraction to another. Although the addition of a dominated strategy, which expanded the basin of attraction of the payoff-dominant equilibrium, induced the players to switch the strategy, after several rounds they fluctuated back to the conventional risk-dominant equilibrium.

Apart from the failure of the theoretical predictions by Basov (2004) and Kim and Wong (2009), an explanation to this outcome could be insufficient number of mutations accumulated by dominated strategy driven by players' rational choices. Due to the obvious inefficiency of the dominated strategy, it was not selected by the players, and thus did not cause changes in their payoffs, which theoretically would support a switch to the payoff-dominant equilibrium.

In the opposite case, the introduction of a dominated strategy, which supports the risk-dominant equilibrium after players' convergence to the payoff-dominant one, was able to promote a definitive transition to the risk-dominant equilibrium. Such transition required several choices of the dominated strategy mistakenly selected by the players.

The results of my experimental work are consistent with the theoretical research by Weidenholzer (2010, 2012) who showed that a risk-dominant equilibrium is robust to the addition and elimination of the dominated strategies if the interaction is sufficiently local. The next step in the testing of relevance of dominated strategies would be adjusting the payoff values, which theoretically could yield a dominated strategy, in order to increase the probability that players choose it. A possible solution would be to disguise inefficiency of the dominated strategy by using higher payoff values or constructing a game where a dominated strategy is dominated in mixed strategies. Such design could stimulate players' choices of a dominated strategy and assist in understanding the relevance the sizes of the basins of attraction on equilibrium selection. Moreover, further research on equilibrium selection in the presence of dominated strategies requires the performance of experiments with a different interaction structure in order to check the theoretical predictions.

Appendix B

Table 6. Frequency of Coordination in the groups 1, 2, 3

	Group 1			Group 2			Group 3		
Period	A	B	C	A	B	C	A	B	C
1	50	50	0	25	75	0	60	40	0
2	37.5	62.5	0	25	75	0	60	40	0
3	87.5	12.5	0	25	75	0	70	30	0
4	75	25	0	25	75	0	70	30	0
5	62.5	37.5	0	50	50	0	70	30	0
6	75	25	0	75	25	0	100	0	0
7	87.5	12.5	0	100	0	0	80	20	0
8	75	25	0	87.5	12.5	0	70	30	0
9	62.5	37.5	0	100	0	0	70	30	0
10	100	0	0	37.5*	62.5*	0*	80	20	0
11	87.5	12.5	0	37.5	62.5	0	80	20	0
12	62.5*	37.5*	0*	62.5	37.5	0	90	10	0
13	37.5	62.5	0	87.5	12.5	0	50*	40*	10*
14	62.5	37.5	0	100	0	0	50	50	0
15	62.5	37.5	0	100	0	0	50	50	0
16	87.5	12.5	0	100	0	0	90	10	0
17	75	25	0	100	0	0	100	0	0
18	100	0	0	100	0	0	90	10	0
19	87.5	0	12.5	100	0	0	80	20	0
20	75	25	0	100	0	0	90	10	0
21	87.5	0	12.5	100	0	0	100	0	0
22	87.5	12.5	0	100	0	0	100	0	0
23	87.5	12.5	0	100	0	0	80	20	0
24	100	0	0	100	0	0	60	40	0
25	100	0	0	100	0	0	50	40	10
26	100	0	0	100	0	0	50	40	10
27	100	0	0	100	0	0	60	40	0
28	100	0	0	100	0	0	100	0	0
29	100	0	0	87.5	12.5	0	100	0	0
30	100	0	0	87.5	12.5	0	100	0	0

* - is the first round of an introduction of a dominated strategy

Table 6. Frequency of Coordination in the groups 4, 5, 6

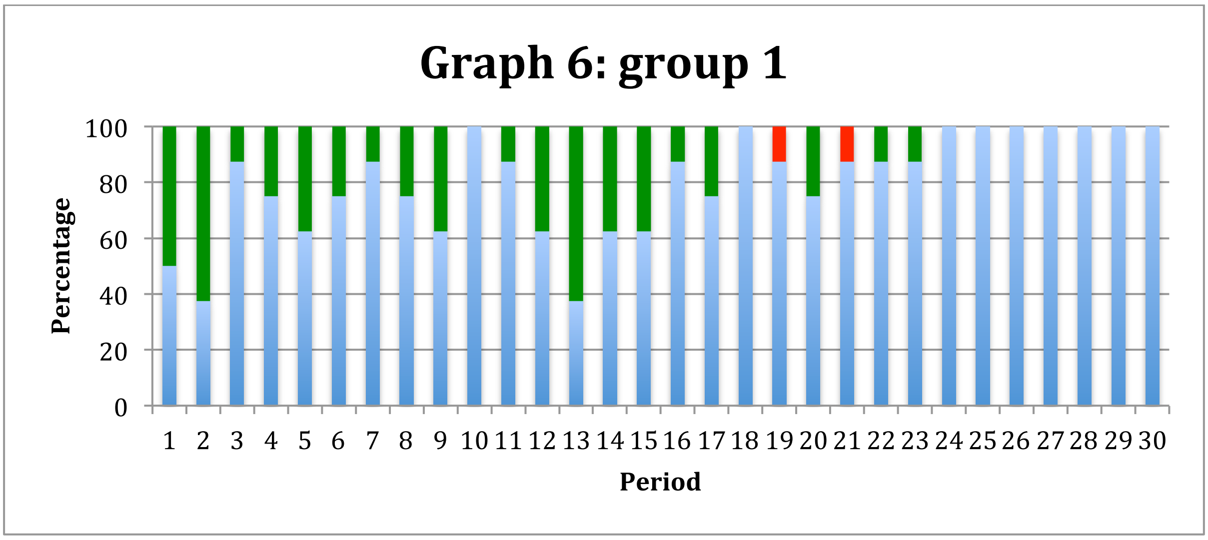
	Group 4			Group 5			Group 6		
Period	A	B	C	A	B	C	A	B	C
1	60	40	0	50	50	0	40	60	0
2	40	60	0	50	50	0	30	70	0
3	40	60	0	50	50	0	30	70	0
4	60	40	0	70	30	0	30	70	0
5	70	30	0	80	20	0	60	40	0
6	80	20	0	90	10	0	70	30	0
7	70	30	0	100	0	0	80	20	0
8	70	30	0	90	10	0	100	0	0
9	90	10	0	90	10	0	90	10	0
10	90	10	0	60*	40*	0*	20*	70*	10*
11	50*	50*	0*	40	60	0	20	70	10
12	20	80	0	40	60	0	30	70	0
13	0	100	0	40	60	0	70	30	0
14	0	100	0	80	20	0	90	10	0
15	0	90	10	90	0	10	90	10	0
16	0	100	0	90	10	0	90	10	0
17	0	100	0	100	0	0	90	10	0
18	0	100	0	100	0	0	100	0	0
19	30	70	0	100	0	0	90	10	0
20	40	60	0	90	0	10	90	0	10
21	70	30	0	100	0	0	80	20	0
22	60	40	0	90	10	0	80	20	0
23	30	70	0	100	0	0	80	20	0
24	20	80	0	100	0	0	90	10	0
25	10	90	0	100	0	0	100	0	0
26	0	100	0	100	0	0	100	0	0
27	0	100	0	100	0	0	100	0	0
28	0	100	0	100	0	0	100	0	0
29	0	100	0	100	0	0	100	0	0
30	0	100	0	100	0	0	100	0	0

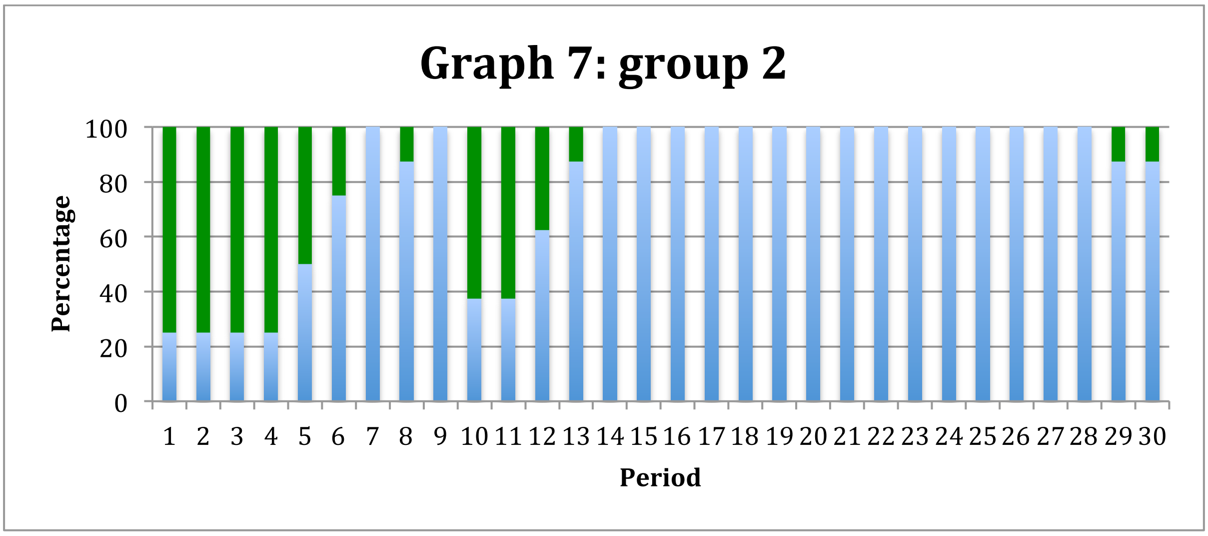
Table 7. Frequency of Coordination in the groups 7, 8

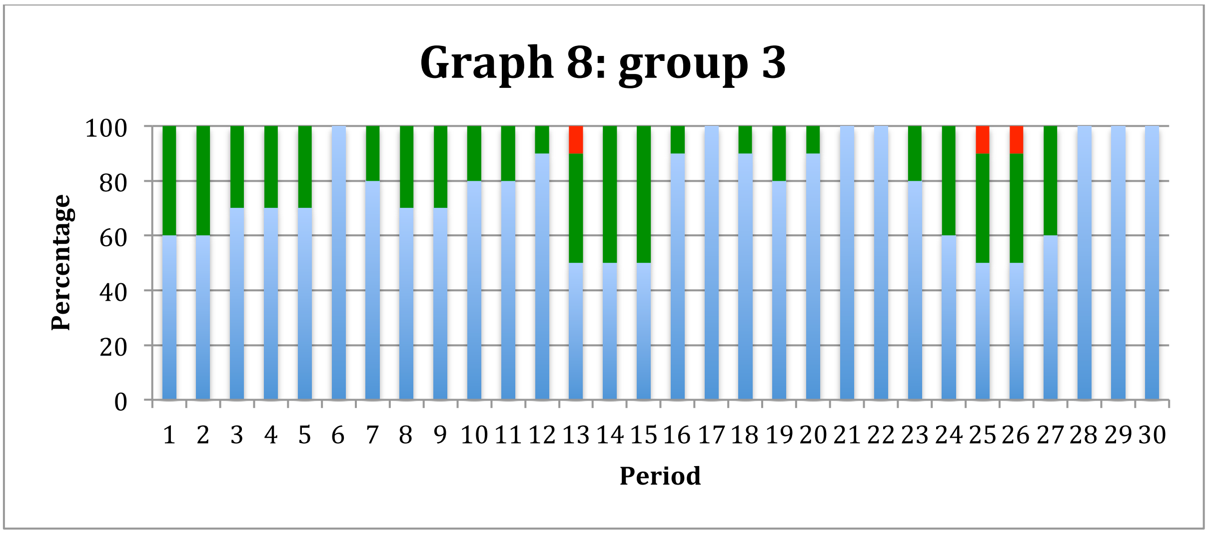
	Group 7			Group 8		
Period	A	B	Z	A	B	Z
1	10	90	0	50	50	0
2	10	90	0	60	40	0
3	20	80	0	60	40	0
4	20	80	0	80	20	0
5	10	90	0	100	0	0
6	10	90	0	100	0	0
7	10	90	0	90	10	0
8	0	100	0	60	40	0
9	0	100	0	30	70	0
10	40*	60*	0*	10	90	0
11	20	70	10	0	100	0
12	60	40	0	30*	40*	30*
13	80	10	10	40	50	10
14	100	0	0	70	30	0
15	90	10	0	60	20	20
16	90	10	0	90	10	0
17	80	10	10	60	30	10
18	100	0	0	80	20	0
19	100	0	0	70	30	0
20	90	10	0	80	20	0
21	80	20	0	80	20	0
22	90	0	10	60	40	0
23	80	0	20	50	50	0
24	90	0	10	30	70	0
25	90	0	10	30	70	0
26	80	0	20	20	80	0
27	90	0	10	10	90	0
28	100	0	0	0	100	0
29	100	0	0	0	90	10
30	100	0	0	20	80	0

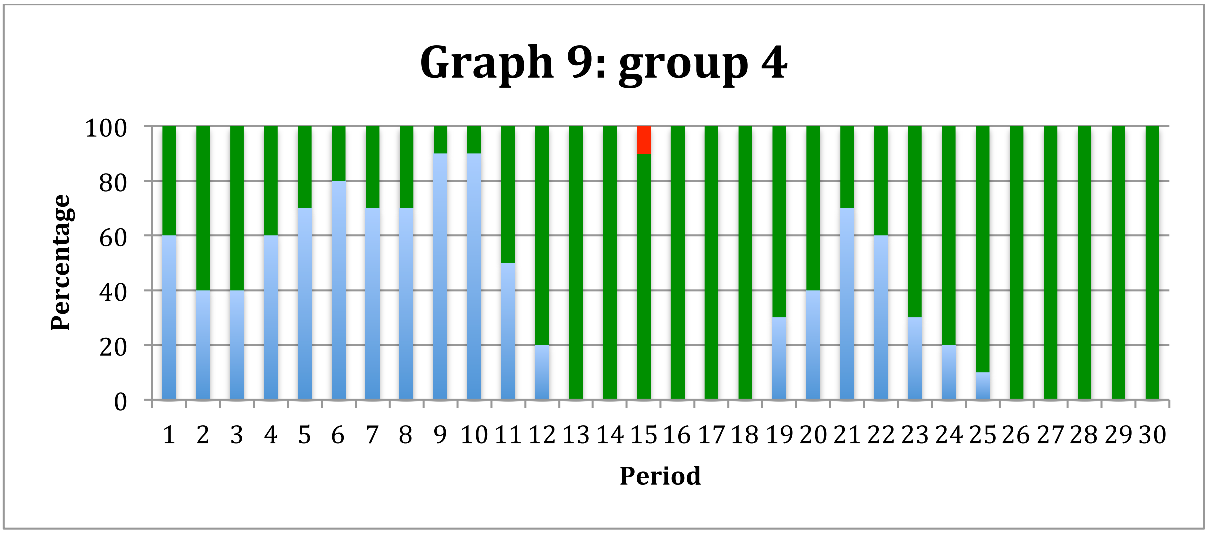
Graphs 6-11. Percentage of the execution of each strategy after an introduction of the dominated strategy C that supports the payoff-dominant equilibrium in groups 1-6.

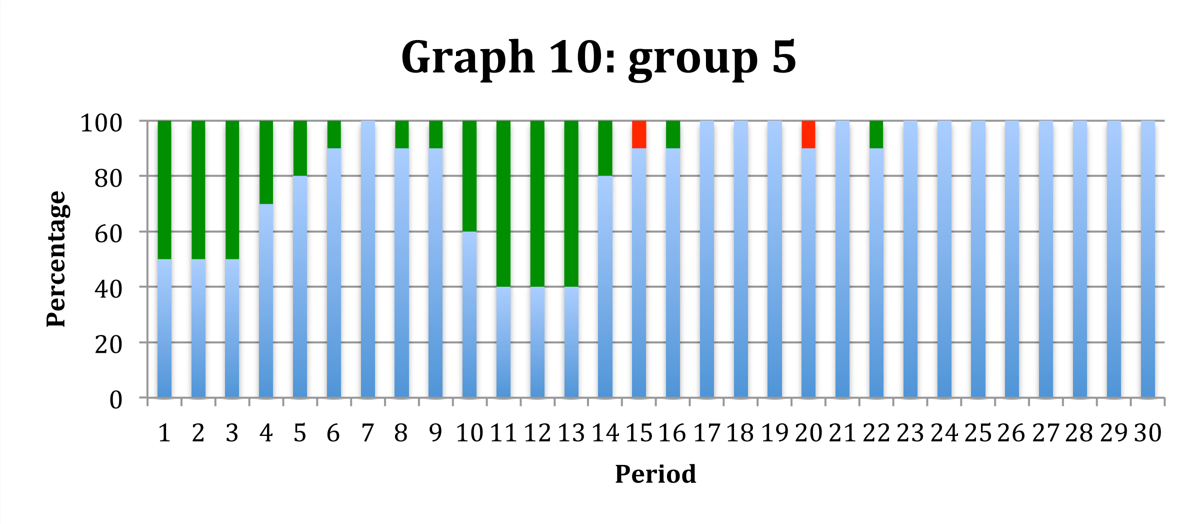
Risk-dominant A **Payoff-dominant B** **Dominated C**

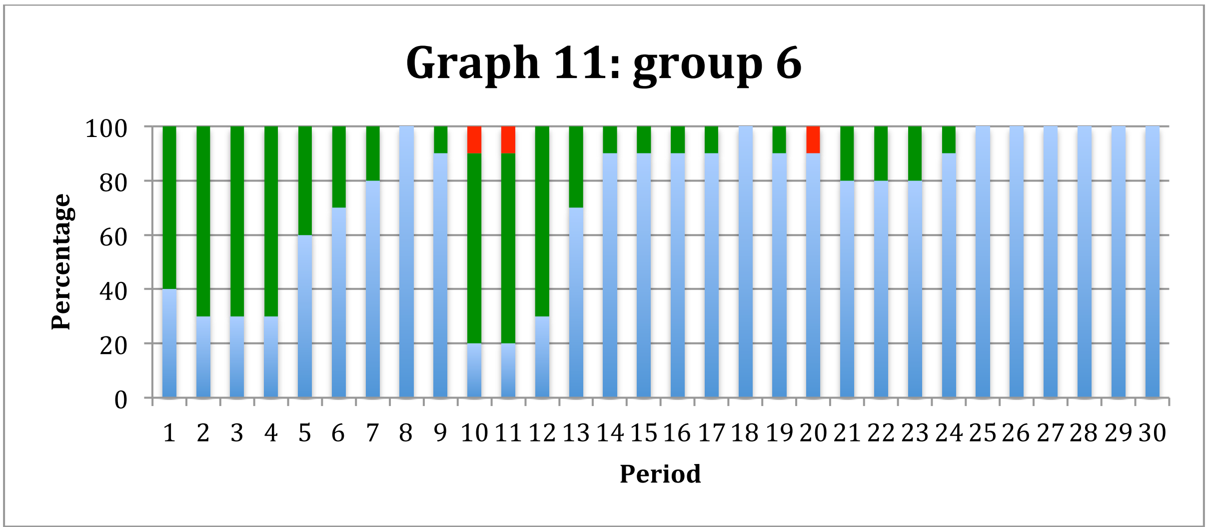




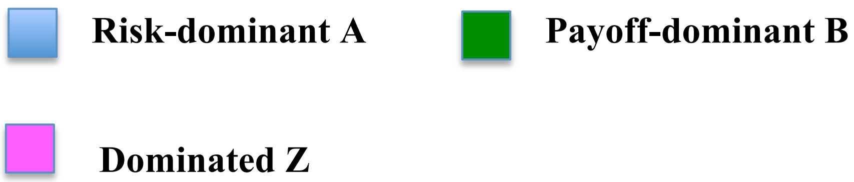

Graph 8: group 3
Percentage
100
80
60
40
20
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30
Period

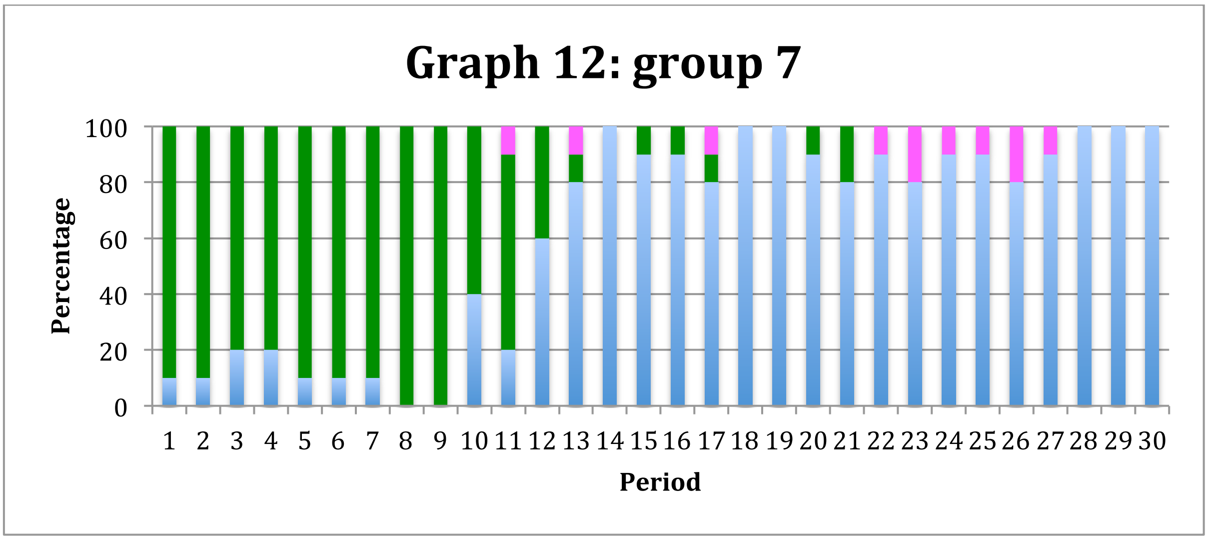

Graph 9: group 4
Percentage
100
80
60
40
20
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30
Period

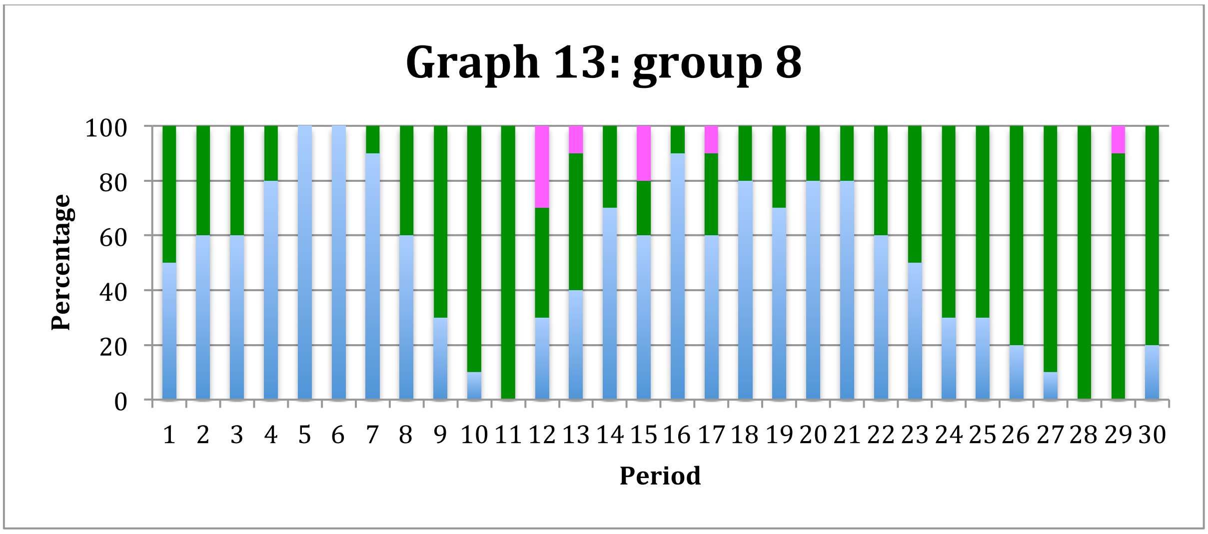

Graph 10: group 5
100
80
60
40
20
0
Percentage
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30
Period


Graph 11: group 6
100
80
60
40
20
0
Percentage
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30
Period

Graphs 12-13. Percentage of the execution of each strategy after an introduction of the dominated strategy Z that supports the risk-dominant equilibrium in groups 7-8.







Concluding Remarks

This dissertation focuses on an experimental approach to an equilibrium selection in evolutionary games. Experimental method is particularly suitable to evaluate the role of various factors for equilibrium selection, particularly, initial conditions, adherence to a conventional equilibrium, risk-dominance or payoff-dominance of the game strategies. Coordination task in this study is considered as a technology adoption process. Obtaining precise data on people's choices in a technology adoption game provides useful foundations for developing appropriate schemes of introduction of innovations to a market.

The literature review, which this work begins with, presented a thorough survey of theoretical and experimental studies starting from the origins of evolutionary games to lock-in processes in technology adoption. Existing research involves various distinct approaches to equilibrium selection, which, as a result, lead to different outcomes. Due to such imprecise conclusions of the reviewed literature, two experiments presented in the Chapters 2 and 3 aimed to investigate equilibrium selection on the basis of stochastic models (Young, 1993; KMR, 1993; Ellison, 1993) and to evaluate the affect of the initial conditions on the final outcome.

Both experiments of the present dissertation include innovative features that serve as a methodological contribution to the experimental design in similar areas. First of all, the peculiarity that distinguishes a technology adoption game from a simple coordination task is a presence of pre-play game rounds. During these rounds players select an equilibrium that afterwards at the moment of an introduction of an innovation performs as a status-quo technology (to tell the truth, there is always a market leader, which is subject to become abandoned after the introduction of a new product). Unlike other experiments on technology adoption (Hossain et al., 2009; Hossain and Morgan, 2010; Heggedal and Helland, 2014), the participants of my experiment choose a conventional equilibrium by themselves, which as it has been demonstrated in the experiment, partially influences their further adoption behavior. In fact, an impossibility to coordinate in the pre-play rounds lead players to accept any introduced strategy, independently of its risk-dominant or payoff-dominant characteristics. On the other hand, a high coordination rate in the pre-play rounds showed a slight tendency of individuals to cherish more the establishment equilibrium.

Second distinctive feature of my experiment is a discovery that an option newly introduced to a game performs as a natural noise. This detail allowed to avoid computerized players or forced actions (as in Corbae and Duffy, 2008). Such intervention acted itself as noise and provoked players to switch away from their status-quo strategy. The introduction of a new strategy perturbed people's choices and nudged them to experiment and as a result to make a few mistakes.

Third and most particular characteristic of the experiments presented in this dissertation, that distinguish them from previous works, is testing equilibrium convergence through transitions. Most authors studying equilibrium selection in evolutionary games perform a long sequence of experimental game rounds and accept the final result. However, according to the path-dependency theory, the initial condition of a population is the crucial factor that determines further development path. Thus, if a population started in a basin of attraction of a particular equilibrium, most probably they will end up in it. In my experiments the introduction of a new strategy intentionally provoked switches out of initial basins of attraction towards the other ones. This method excludes the possibility to remain in the absorbing state, accelerates convergence and assists in collecting more data on population's behavior.

The results of the first experiment on technology adoption have confirmed the reliability of the predictions of KMR model (1993): risk-dominance of a strategy was detected to be a paramount selection factor for the players matched in a global network. However, the results of the same game played in a local matching network lead to an efficient outcome: as it was expected, local interaction promoted players convergence to the payoff-dominant equilibrium. In all of the cases the introduction of a new strategy attracted players' choices and provoked switches. Although the KMR (1993) predictions based on the sizes of the basins of attraction are fairly accurate, payoff-dominance and risk-dominance of the introduced strategy played more important role than the initial conditions. The experimental evidence has shown that the probability to remain in the starting risk-dominant basin of attraction is a bit higher than predicted by KMR (1993), while a start in the payoff-dominant basin of attraction converges to payoff-dominant or payoff-dominant equilibrium with equal probability.

The experiment in the Chapter 2 developed the theme of the absorbing basins of attractions from another point of view. It aimed to determine whether an expansion of a basin of attraction of a particular equilibrium through an addition of a dominated strategy might induce players to switch to it. In general, the results of the second experiment suggested that players converge to a risk-dominant equilibrium. An addition of a dominated strategy, which was supposed to support a switch from the established conventional risk-dominant equilibrium to a payoff-dominant equilibrium by enlarging its basin of attraction, had no positive results. A switch from the pre-play conventional payoff-dominant equilibrium to the risk-dominant equilibrium after an addition of a dominated strategy supporting its selection took place in the experiment. However, limited number of such observations does not allow us to make inference about validity of this result.

Further work could be concentrated on the extensions these experiments. Particularly, the second experiment could be performed with more treatments and include different matching methods, which have demonstrated their extreme importance in equilibrium selection. Moreover, the dominated strategy, added to the game could be designed in different ways, for instance it could be dominated in mixed strategies. The payoffs that the dominated strategy yields should be chosen very precisely since they might have a great impact on players' choices.

In general, this dissertation has pointed out the essential factors of equilibrium selection in evolutionary games, which is risk-dominance for global matching and payoff-dominance in local matching network. Although a conventional equilibrium established during the pre-play had a slight influence on players' further choices, an introduction of a new strategy always provoked switches. Considering it in the light of an adoption of a new technology, a lock-in on inefficient technology is an extremely unlikely event. However, the presence of path-dependence and a tendency to select a riskless equilibrium detected in the global matching treatments, justifies some degree people's conservatism. For this reason, this thesis may provide some implications for the marketing studies: in case there is a strong market leader an introduction of a new competitive product should be performed gradually, from the most promising circles upwards to the masses.

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