Department of Mathematics and Systems Analysis

Cooperation, commitment, and other-regarding behavior in duopoly games

Ilkka Leppänen

Aalto University

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Abstract

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Abstract

Firms and other economic actors often forgo own advantage and instead display other-regarding preferences. This Dissertation studies the reasons for this behavior in the context of duopoly games using laboratory experiments and analytical models. We develop new results concerning behavior in duopoly games under imperfect commitment and incomplete information and when interactions are repeated. We also show that the interplay of conjectural variations and other-regarding preferences has novel implications for behavior in strategic interactions.

The behavioral methods used in the Dissertation include standard laboratory experiments as well as psychophysiological methods that allow correlating laboratory behavior to activation of the autonomic nervous and skeletomuscular systems. The analytical methods include evolutionary game theoretic models where evolutionarily stable strategies are sought in finite and infinite size populations and standard game theoretic equilibrium analysis where conditions for uniqueness of subgame-perfect equilibria are sought in extensive form games of incomplete information.

The objectives of the Dissertation are to provide experimental evidence on the role of costless commitment via cheap talk, private information, and emotions in cooperation in duopoly games. The objectives are also to provide new analytical results on the interplay of other-regarding behavior and conjectural variations and to examine how asymmetric and stochastic private information affects commitment. The overall theme of the Dissertation is to study how variations on the assumption of own payoff maximization affect players' behavior in duopoly games.

The results suggest that imperfect commitments, such as cheap talk announcements and partial commitments, have value in strategic interactions. However, the effects of costless or partial commitments depend on available information about payoffs or marginal costs. We also find that cooperative behavior in repeated duopoly games has an emotional foundation. This is shown e.g. by emotional expressions when observing decision outcomes and by autonomic activity during decision making. Our studies on other-regarding preferences in conjectural variations models suggest that taking these both into account and allowing evolutionary selection leads to novel results. These include the explicit dependence of the evolutionarily stable conjecture on the other-regarding preference parameter and the evolutionary stability of self-regarding behavior with consistent conjectures. We suggest several avenues for future experimental and analytical research.

Keywords duopoly games, behavioral experiments, neuroeconomics, evolutionary games

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Tiivistelmä

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Ilkka Leppänen

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Tiivistelmä

Yritykset ja muut taloudelliset toimijat jättävät usein käyttämättä mahdollisuuksia saavuttaa omia hyötyjään ja sen sijaan käyttäytyvät toiset toimijat huomioiden. Hyödyntäen laboratoriokokeita ja analyyttisia menetelmiä tässä väitöskirjassa tarkastellaan tämän käyttäytymisen syitä duopolipeleissä. Esitämme uusia tuloksia käyttäytymisestä duopolipeleissä kun sitoutuminen ja informaatio ovat epätäydellisiä ja kun kohtaamiset ovat toistettuja. Näytämme myös että uskomusmuunnelmamallien ja toiset huomioivien preferenssien mallien vuorovaikutus tuottaa uudenlaisia päätelmiä käyttäytymisestä strategisessa vuorovaikutuksessa.

Väitöskirjan behavioraalisia menetelmiä ovat laboratoriokokeet ja psykofysiologiset menetelmät jotka mahdollistavat behavioraalisten havaintojen korreloimisen aktivaatioon autonomisessa hermostossa ja kasvojen lihaksistossa. Analyyttisiä menetelmiä ovat evolutiiviset pelimallit joissa haetaan stabiileja strategioita ääretön- ja äärelliskokoisissa populaatioissa sekä standardit peliteorian mallit joissa haetaan yksikäsitteisyysehtoja osapelitäydellisille tasapainoille laajennetun muodon epätäydellisen informaation peleissä.

Väitöskirjan tavoitteina on tarjota kokeellista näyttöä tyhjään puheeseen perustuvan kustannuksettoman sitoutumisen, yksityisen informaation, ja emootioiden rooleista duopolipeleissä. Tavoitteina on myös tuottaa uusia tuloksia uskomusmuunnelmien ja toiset huomioivien preferenssien vuorovaikutuksesta ja tarkastella miten epäsymmetrinen ja epävarma yksityinen informaatio vaikuttaa sitoutumiseen. Väitöskirjan läpikantavana teemana on tutkia miten oman tuoton maksimoimisen olettamuksen muuntelu vaikuttaa pelaajien käyttäytymiseen duopolipeleissä.

Tulokset osoittavat että epätäydellisen sitoutumisen keinoilla kuten tyhjällä puheella ja osittaisella sitoutumisella on vaikutuksensa strategisessa päätöksenteossa. Näiden keinojen vaikutukset riippuvat kuitenkin saatavilla olevasta informaatiosta koskien tuottoja tai rajakustannuksia. Väitöskirjassa myös osoitetaan että yhteistyökäytöksellä toistetuissa duopolipeleissä on emotionaalinen perusta. Tämän osoittavat mm. kasvojen tunneilmeet pelien tuloksia havaittaessa ja autonomisen hermoston aktivaatio päätöksiä tehtäessä. Tulokset toiset huomioivista preferensseistä uskomusmuunnelmamalleissa osoittavat että uskomus voi riippua eksplisiittisesti preferenssiparametrista ja itsekäs käytös voi olla evolutiivisesti stabiilia kun uskomusmuunnelma on konsistentti. Väitöskirjassa ehdotetaan useita jatkotutkimusaiheita kokeelliselle ja analyyttiselle tutkimukselle.

Avainsanat duopolipelit, behavioraaliset kokeet, neurotaloustiede, evolutiiviset pelit

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Papers

I. Hämäläinen, R.P., Leppänen, I. 2016. Cheap talk and cooperation in Stackelberg games. *Central European Journal of Operations Research.* doi:10.1007/s10100-016-0444-9. (25 pages)

II. Leppänen, I., Hämäläinen, R.P. 2015. Emotions in a repeated Cournot duopoly game: A psychophysiological experiment. *Manuscript.* (36 pages)

III. Leppänen, I. 2016. Evolutionarily stable conjectures and other-regarding preferences in duopoly games. Revision requested by *Journal of Evolutionary Economics.* (28 pages)

IV. Leppänen, I. 2016. Consistent conjectures and the evolutionary stability of other-regarding preferences. *Economics Letters*, Vol. 142, pp. 53–55. doi:10.1016/j.econlet.2016.03.004.

V. Leppänen, I. 2016. Partial commitment in an endogenous timing duopoly game with asymmetric and uncertain costs. *Manuscript.* (27 pages)

Contributions of the author in Papers I and II

In Paper I, Leppänen and Hämäläinen shared work in designing the experiments, analyzing data, and writing. Leppänen conducted the experiment.

In Paper II, Leppänen and Hämäläinen shared work in designing the experiment. Leppänen conducted the experiment, analyzed the data, and wrote the text and Hämäläinen provided comments.

Vendin muistolle

Preface

This Dissertation was made possible by the many people whom I have the privilege to acknowledge here.

First I want to thank Professor Raimo P. Hämäläinen for all his efforts in supervising and instructing the work that led to this Dissertation. His guidance on writing papers, endless amount of ideas, and enthusiasm on research in general greatly contributed to the Dissertation. It would not have been possible for me to finish the papers in the Dissertation without working at Professor Hämäläinen's research group.

I also want to thank Professor Esa Saarinen for his guidance at the early stages of my career. The seminars on creative problem solving organized by Professors Saarinen and Hämäläinen led me to doctoral studies. I have also benefited from inspiring discussions on game theory with Professor Harri Ehtamo. I also want to thank the preliminary examiners, Professors Topi Miettinen and Marco Piovesan, for their insightful comments.

Many colleagues at the Systems Analysis Laboratory deserve acknowledgement for their company in Monday seminars and doctoral programme trips and for acting as subjects in our pilot experiments. I learned a lot about teaching from Professor Juuso Liesiö and about the social sides of university work from Dr. Antti Punkka. Dr. Mikko Viinikainen provided indispensable aid with the psychophysiological measurements. I have greatly enjoyed the statistical and science-philosophical discussions with Tuomas Lahtinen.

I want to thank my parents, brothers, and my extended family for their continuing support. My final thanks go to my wife Vera who has stood by me all these years.

Espoo, June 23, 2016

Ilkka Leppänen

Contents

1 Introduction

Firms and other economic actors often demonstrate behavior that is not solely own-payoff maximizing. For example, in strategic delegation owners incentivize managers to maximize market share or relative profits [Vickers, 1985], and in mixed oligopoly the market includes a welfare-maximizing public firm [De Fraja and Delbono, 1989]. Often the behavior is other-regarding without any specific motive such as state monopoly. An explicit statement of this behavior was given in 2004 by the internet company Google in its S-1 prospectus[1] when it listed in the NASDAQ:

> ”We believe strongly that in the long term, we will be better served—as shareholders and in all other ways—by a company that does good things for the world even if we forgo some short term gains.”

This Dissertation aims to answer the question of why firms and other economic actors do such ”good things”, cooperate with other actors, and voluntarily forgo attainable own payoffs. We examine this question using a combination of behavioral and analytical methods.

1.1 Objectives of the Dissertation

The Dissertation examines duopoly behavior from the perspectives of cooperation, commitment, and other-regarding preferences. The objectives are to provide experimental evidence on the role of costless commitment via cheap talk, private information, and emotions in cooperation in duopoly games. The objectives are also to provide new analytical results on the interplay of other-regarding behavior and conjectural variations, and examine how asymmetric and stochastic private information affects commitment. The overall theme of

[1] Retrieved from United States Securities and Exchange Commission, http://www.sec.gov/Archives/edgar/data/1288776/000119312504073639/ds1.htm (March 23, 2016)

the Dissertation is to examine, by using multiple methods, how variations on the assumption of own payoff maximization affect players' behavior in duopoly games.

1.2 Research methods and structure

We use laboratory experiments in two of the papers and analytical game theoretic modeling in three of the papers. Papers I and II are experimental studies. Paper I reports the results of a conventional behavioral experiment, whereas the experiment in Paper II correlates behavioral and psychophysiological observations. In both experimental papers we use generalized linear mixed models to analyze the observations. Papers III and IV are analytical studies that use evolutionary game theory modeling. In Paper III the concept of evolutionarily stable strategy is used in an infinite population. In Paper IV the concept of large population evolutionarily stable strategy is used in a finite population. Paper V is an analytical study that uses standard game theory equilibrium analysis to formulate conditions for the uniqueness of subgame-perfect equilibria in extensive-form games of incomplete information.

The Dissertation consists of the Summary and Papers I–V. The Summary introduces literature, reviews the research results obtained in the Papers I–V and discusses their theoretical implications, and provides avenues for further research.

2 Literature

2.1 Duopoly games and other-regarding preferences

The duopoly game formulation originates from Cournot [1838/1988] and it was extended by Bertrand [1883/1988]. Cournot introduced the concept of a demand curve and examined the competition of producers. Bertrand examined price competition and included the consumer as a strategic player. Nash [1951] provided an existence result concerning equilibria in general n-player games in mixed strategies. The related equilibrium concepts are often called Cournot-Nash in quantity competition and Bertrand-Nash in price competition.

Although the models of Cournot, Bertrand, and Nash as well as the various models of strategic interaction that build upon them consider own payoff maximization as the sole firm objective, empirical and laboratory evidence shows that the motivations for behavior in strategic decision making situations are not so straightforward. Tacit collusion among few competitors is one well-known phenomenon that cannot be explained by a model where firms maximize their stage game payoffs. Laboratory oligopoly games are another. Fouraker and Siegel [1963], who were among the first to study oligopoly behavior experimentally, found that subjects care about fairness, reciprocity, but also of rivalry. Later experimental literature on the Counot duopoly game has reported many kinds of outcomes ranging from cooperative to competitive [for reviews see Holt, 1995 and Potters and Suetens, 2013].

A duopoly game has two players, indexed by $i = 1, 2$, with continuous strategies x_i on the real line. Whenever we refer to a player we use the index i, and the index $j \neq i$ is used to denote the other player. The payoff functions are denoted $f_i(x_i, x_j)$ and we can assume without the loss of generality that they admit values from the positive real line $\mathbb{R}^+$. The strategy sets and payoff functions are common knowledge.

Other-regarding preferences (ORPs) can be taken into account in the game by having the players maximize utility functions $u_i(f_i, f_j)$ that map the feasible payoff pairs to the real line. The utility functions thus represent preference orderings on $\mathbb{R}^+ \times \mathbb{R}^+$. In this way, we do not rule out the possibility that the players do not solely maximize their own payoff functions without regard to how the market payoffs are distributed among them. Assuming that the first derivatives of the utility functions exist, the first-order condition of the utility maximization problem of player i is

$$\frac{\partial}{\partial x_i} u_i(f_i(x_i, x_j), f_j(x_i, x_j)) = 0. \tag{1}$$

As there are two such equations defining the first-order conditions, these equations implicitly define the equilibrium strategies x_i^* for $i = 1, 2$.

A parsimonious model of linear ORPs for player i, used in Papers III and IV of this Dissertation, is given by

$$u_i(f_i, f_j) = f_i + tf_j. \tag{2}$$

For $t = 0$ the players are self-regarding and maximize their own payoffs. For $t > 0$ they are benevolent or altruistic. For $t < 0$ they are malevolent. A desirable feature of (2) as a model of other-regarding behavior is that it is computationally easy to handle in the first-order conditions. A shortcoming is that it does not allow the preferences to be different for different relative payoff comparisons. For example, a player may evaluate differently a payoff distribution where the player itself has an advantage than a payoff distribution where the other player has an advantage. In the Fehr and Schmidt [1999] model of inequality aversion (henceforth the "F&S model") player i maximizes a utility function

$$u_i(f_i, f_j) = f_i - t_i \max\{f_j - f_i, 0\} - t_i' \max\{f_i - f_j, 0\}, \tag{3}$$

where $0 \leq t_i' < 1$ and $t_i' \leq t_i$. The parameter t_i is now referred to as the disadvantageous inequality aversion parameter and t_i' is the advantageous inequality aversion parameter.

In sequential-move games the F&S model is relatively easy to estimate from experimental observations using econometric methods, but it is analytically complicated [see e.g. Doruk and Santos-Pinto, 2014]. One reason for this is that it has piecewise-linear indifference curves and best-response correspondences. More importantly, the F&S model cannot account for changing reciprocal preferences for different opportunity sets when these opportunity sets are parabolic, as in linear-quadratic payoff functions. By opportunity sets we mean the sets of possible payoffs that the first moving player makes available for the second moving player. Cox et al. [2008] present a nonparametric model of ORPs that can be estimated from behavioral data by defining the willingness-to-pay (WTP) of own payoffs in exchange of a unit increase or decrease in the other's payoffs. In fixed and linear preferences, WTP is constant for all feasible opportunity sets, whereas the Cox et al. [2008] model allows WTP to change as function of the opportunity set. This model also accounts for intentions that are revealed by the choice of the opportunity set and it thus unifies the ideas of distributional preference models such as F&S and intention-based models such as Rabin [1993]. A shortcoming of the Cox et al. [2008] model is that it is only applicable to sequential moves. We estimate the model of Cox et al. [2008] in Paper I.

In a sequential-move duopoly game one player chooses its strategy first and the other player chooses its strategy after observing the first mover's choice. In such a case the first mover (or leader) can optimize its strategy against the second mover's (or the follower's) strategy. The original formulation of a sequential move duopoly game is due to Von Stackelberg [1934]. An intuitive example of Stackelberg competition is when the leader has the ability to produce a given amount of a product into the market and the follower has to accommodate the leader's quantity. However, as is well known from experiments on ultimatum and dictator games, players in sequential move games care about payoff distributions [Camerer, 2003]. This is also intuitive to understand in the Stackelberg duopoly via the F&S model. Let us denote the Stackelberg leader's equilibrium strategy x_L^* and the follower's equilibrium strategy x_F^*. Because the leader has the first-mover advantage, we have $f_L(x_L^*, x_F^*) > f_F(x_L^*, x_F^*)$. If the follower maximizes a utility function (3) with the disadvantageous inequality aversion parameter $t_F > 0$, then it experiences a reduced utility in (x_L^*, x_F^*). Therefore the follower's reaction to the leader's strategy demonstrates reciprocity. This can be seen from an example where we have $f_i = x_i(a - x_i - x_j)$ for $i = L, F$, where $a > x_L + x_F$ is a market demand parameter. The first-order condition for the follower's utility maximization problem is then

$$\frac{\partial}{\partial x_F} u_F(f_L(x_L, x_F), f_F(x_L, x_F)) = (1 + t_F)(a - 2x_F) - x_L = 0$$

from which we can solve $x_F^*(x_L) = (a + at_F - x_L)/(2 + 2t_F)$. As t_F increases, the slope of $x_F^*(x_L)$ becomes less steep.

It is important to observe that even with self-regarding preferences the leader is solving a payoff maximization problem that is different from the one proposed by Cournot, Bertrand, and Nash [Heifetz et al., 2007]. This is because the Stackelberg leader does not treat the follower's strategy as a constant but as a function that depends on the leader's own strategy. Consistent with the models of ORPs, laboratory evidence on the Stackelberg duopoly game has found that both the leader has a tendency to behave altruistically and the follower has a tendency to reciprocate the leader [Huck et al., 2001, Cox et al., 2008, Lau and Leung, 2010].

The Stackelberg leader's possibility to optimize against the follower's strategy is an example of the use of commitment to gain own advantage. However, whether the leader or the follower is at an advantage depends crucially on whether the reaction functions are downwards sloping or upwards sloping [Hamilton and Slutsky, 1990]. In the Stackelberg game with quantity competition the strategies are substitutes to each other and the reaction functions slope down. In this case the first moving player is at an advantage when compared to the second moving player. In price competition the strategies are generally complements (except for homogenous products) and reaction functions slope upwards. Then the second-mover has an advantage over the first-mover. Hamilton and Slutsky [1990] show that the players face a coordination dilemma when their reaction functions slope up and when they establish their timing by announcements. In an asymmetric cost case this coordination dilemma can be resolved by a risk dominance argument where the players aim to minimize their coordination failure risks [Amir and Stepanova, 2006]. We show in Paper V of this Dissertation that this coordination dilemma can also be resolved by partial commitments where the players are imperfectly bound to their timing announcements, given that there is an asymmetry in marginal cost distributions.

The sequential move game is not the only avenue for reciprocity. Reciprocity may arise in repeated interactions even when the stage games are in simultaneous moves. This is because if a player deviates from an established cooperative (Pareto-dominant) outcome on round t, then the other player can observe this deviation on round $t + 1$ and punish by deviating to the stage game Nash equilibrium. The Folk Theorem formalizes the idea that cooperative outcomes can be supported as equilibria in a repeated game under various scenarios, such as discounting under an infinite horizon [Fudenberg and Maskin, 1986]. However, the Folk Theorem provides an instrumental motivation to behavior: Cooperation and the trigger strategies that support it are used only as instruments to attain maximal own payoffs [Sobel, 2005]. The Folk Theorem dismisses the intrinsic motivations that players may have from cooperating.

2.2 Neuroeconomics

One of the problems of deducing the players' intrinsic motivations from behavioral data is that these motivations may be confounded by other variables than those under direct observation. The repeated duopoly game provides an example. It is a well established empirical regularity that players in repeated interaction cooperate. It is also well known that sometimes players in one-shot interactions cooperate [Holt, 1995]. Therefore, the Folk Theorem cannot be the sole explanator of cooperation. However, it is impossible to deduce only from behavioral observations why players cooperate in the repeated duopoly game because the possible other-regarding motivation is confounded by the Folk Theorem motivation.

Due to the technological advancement in neuroimaging and psychophysiological methodology, it was inevitable that researchers would turn to correlating the events in the human nervous and skeletomuscular systems with behavior in economic experiments. This development gave rise to the field of neuroeconomics [see e.g. Camerer et al., 2005]. The obvious advantage of the neuroeconomics methodology over subject self-reports is its objectivity: Self-reports tend to be biased [Babcock and Loewenstein, 1997], are prone to experimenter demand effects [Zizzo, 2010], and are difficult to incentivize. The methodology also helps overcome the aforementioned confound. By studying the psychophysiological correlates of behavior in repeated interaction we can directly deduce whether cooperation is self-regarding or other-regarding. This is what we do in Paper II of this Dissertation.

From the neurobiological viewpoint decision making is interaction between two systems within the brain. These are often termed the emotional and cognitive systems or the automatic and controlled systems [Loewenstein and O'Donoghue, 2004, Bechara and Damasio, 2005, Camerer et al., 2005]. The emotional system consists of primitive brain parts, such as the anterior insula, thalamus, amygdala, and hippocampus, that are more ancestral than the parts of the primate cognitive system comprising mostly of the prefrontal cortex. The emotional system is responsible for decisions that require a low level of deliberation. The traditional conception of "rational" decision making relies solely on the cognitive system and emotions or automatic processing have no role in it [Chang and Sanfey, 2008]. Due to the connectedness of the prefrontal cortex to other brain areas the cognitive system can override the emotional system when needed [Miller and Cohen, 2001]. Brain imaging studies suggest that both the prefrontal cortex (cognitive system) and the anterior insula (emotional system) are activated in situations involving other-regarding behavior [Sanfey et al., 2003, Knoch et al., 2006, Baumgartner et al., 2011] and less strategic tasks such as moral judgements [Koenigs et al., 2007].

Emotions, or autonomic behavior more generally, are central to animal behavior. Even simple invertebrates have autonomic defence mechanisms against their predators [Porges, 2011]. The word emotion stands for something that motivates animals for action. Emotions are thus necessary physiological responses to events that require motivated behavioral reactions. Activity in the brain's emotional system is manifested by activation of the autonomic nervous system (ANS). Emotions, alongside cognition, are also necessary components of social decision making in humans. Adam Smith [1790] referred to "moral sentiments" when discussing emotions in economic behavior. Frank [1987] argues that observable emotional states such as anger have pre-commitment value in economic interactions.

Because of human sociality, emotions have communication value and can be observed from facial expressions. The evolutionary origins of basic human emotional expressions were laid out by Charles Darwin [1872]. Later research has recognized that many discrete emotional expressions have a functional origin. For example, by oral rejection the disgust expression defends the body against toxicity [Chapman and Anderson, 2012]. Of the two basic negative emotions that we study in Paper II of this Dissertation, anger motivates the subject to approach a transgressor [Carver and Harmon-Jones, 2009] whereas disgust motivates withdrawal [Chapman and Anderson, 2012]. Positive affect, the one positive emotion that we study, has a nonspecific motivational tendency [Fredrickson, 2004], but it is known to relate to prosocial attitudes [Mehu et al., 2007], success in competition [Matsumoto and Willingham, 2006], and punishing social norm violators [Rilling et al., 2008].

The basic emotions are well defined in psychology but often used interchangeably outside the psychological domain. For example, anger and disgust are often used to describe the same negative emotion [Nabi, 2002]. In formal models of other-regarding behavior the social emotions such as resentment (anger/disgust) and gratitude (happiness) and ORPs are often taken to mean the same thing [see e.g. Cox et al., 2007, p. 18]. Recognizing the functional origins of different emotions and studying their involvement in economic behavior helps clarifying the somewhat vague lay meaning of the emotional terminology.

2.3 Conjectures, beliefs, and evolution

The conjectural variations concept has historical roots in the formal analysis of competitive interactions [Bowley, 1924]. A conjecture denotes player i's belief about the variation of player j's strategy $x_j(x_i)$ as player i changes its strategy x_i by one unit. In conventional models (also called zero conjectures or Nash conjectures) player i believes that player j's strategy x_j is constant for all x_i. The conjecture can be implicitly defined in the payoff maximization problem by writing the first-order condition for payoff maximization using the total derivative:

$$\frac{d}{dx_i} f_i(x_i, x_j) = \frac{\partial}{\partial x_i} f_i(x_i, x_j) + \frac{\partial}{\partial x_j} f_i(x_i, x_j) \frac{dx_j}{dx_i} = 0,$$

where $\frac{dx_j}{dx_i} \triangleq r_i$ is player i's conjecture. As the conjecture r_i is varied between positive and negative values, a host of relevant behavioral situations can be represented, from perfect competition to Cournot competition. The conjectural variations model is often seen as unifying the various models of industrial organization [Daughety, 1988]. The Nash conjecture has $r_i = 0$ for $i = 1, 2$ and thus the conjectural variations model nests the standard payoff maximization model as a special case. The established conjectural concept is the consistent conjecture which equals the reaction function slope at the equilibrium. Thus, consistency combines individual rationality (choose by the best response) and correctness (conjecture correctly that the other chooses by its best response) [Bresnahan, 1981].

The conjectural variations concept, however, has fundamental epistemic flaws. It imposes dynamics in a static framework: Because the game is static, it is impossible for the players to have anything but zero beliefs about each others' reactions [Lindh, 1992]. The main shortcoming of the consistent conjecture concept is that the outcome predicted by equilibrium analysis that recognizes consistent conjectures (the consistent conjectures equilibrium, CCE) is not an equilibrium in nondominated strategies [Daughety, 1985]. Therefore, CCE is not suitable as a Nash equilibrium refinement. The concept has later been recognized as a useful shortcut to complicated dynamic games [Cabral, 1995] as well as a model where behavior is boundedly rational and learning takes place [Jean-Marie and Tidball, 2006]. Conjectural variations also enjoy popularity in empirical analysis of industrial organization [see e.g. analysis of electricity spot markets in Wolfram, 1999].

Even though the empirical literature on conjectural variations is rich, the concept has not received further experimental validation as a model of beliefs. To our knowledge there exists only one experiment that compares the consistent conjectures concept to the Nash conjecture, that of Holt [1985]. In his experiment, Holt [1985] used a Cournot market with a payoff matrix. The hypothesis testing was made based on behavioral observations, and the CCE hypothesis was rejected. As we previously argued, the behavioral economics literature has since developed many models that take ORPs into account. Holt was also aware of this possibility and asked cursorily if consistent conjectures together with distributional maximization could lead to the observed results, but found that a linear model of ORPs such as (2) would not change the consistent conjecture of the game.[2] However, this does not necessarily refute the consistent conjectures concept: Lau and Leung [2010] have shown that in experimental Stackelberg markets reaction functions are piecewise linear, and Cox et al. [2008] have shown that a nonlinear model of ORPs fares best against a variety of competing models, including the piecewise linear F&S model. Therefore, it is possible that a consistent conjecture would be differently formulated if the ORP model would assume a more general, nonlinear form.

Belief modeling under bounded rationality [see e.g. Nagel, 1995, Camerer et al., 2004, Costa-Gomes and Weizsäcker, 2008] is a related approach to conjectural variations. What is special about the conjectural variations approach as a belief model is that they are not b eliefs

[2] To be precise, Holt only computes the consistent conjecture with ORPs, not the outcome of the game with the consistent conjectures. The outcome with ORPs and consistent conjectures is calculated in Paper III of this Dissertation. Holt also had a low number of pairs, 6, in the single-period duopoly experiment.

about a single action of the other player but beliefs about the whole reaction correspondence to set-valued own strategies. Güth et al. [2012] assume that boundedly rational players have aspiration levels about their own profits that also include a conjecture about the strategies of the other players. These profit aspirations have the "variational" feature of conjectural variations, i.e. they are not merely point beliefs.

Evolutionary models in game theory and economics fall into the category that explains strategic behavior with bounded rationality. Evolutionary models assume bounded rationality because the players in repeated or overgenerational interaction maximize their short-term fitness and not the present value of the payoff stream that extends over the foreseeable horizon. Evolutionarily stable preference types (say, conjectures r_i or ORP parameters t_i) are types that maximize fitness in a process of dynamic adjustments [Friedman, 1991]. The fitness function given types t, t' is defined via the payoff function at the equilibrium, $f(t, t') = f_i(x_i^*(t, t'), x_j^*(t, t'))$, where x_i^*, x_j^* are the equilibrium strategies for $i, j = 1, 2$, $i \neq j$. A type (or more generally a state) is evolutionarily stable if it can resist the invasion of mutants, in the sense that

$$f(t^*, t^*) > f(t, t^*) \tag{4}$$

or

$$f(t^*, t^*) = f(t, t^*), \quad f(t^*, t) > f(t, t), \tag{5}$$

for all t, where t^* is the evolutionarily stable type and t is a mutant type. The condition (4) states that the evolutionarily stable type resists all mutants. The condition (5) states that even if one mutant has a fitness equal to the evolutionary stable type, proliferation of mutants does not lead to their superior fitness. The Maynard Smith [1982] model assumes that the population of players is of infinite size, whereas the models of Schaffer [1988] and Neill [2004] assume a finite population size. In the latter case the conditions for evolutionary stability (4,5) need to be modified appropriately (see Müller and Normann, 2007, or Paper

IV of this Dissertation).[3]

Firms in perfect competition survive in evolution by maximizing own profits, but as Schaffer [1989] shows, deviations from profit maximization can be evolutionarily stable when firms have market power. The same idea has later been developed in the indirect evolutionary approach—where preferences influence behavior which determines fitness which in turn regulates the evolution of preferences—by Bester and Güth [1998]. Müller and Normann [2005] show that the indirect evolutionary approach "rationalizes" the consistent conjecture if we assume that the players hold zero ORPs. However, if the ORPs are nonzero, the consistent conjecture is not the conjecture that is evolutionarily stable. Paper III of this Dissertation shows that then the evolutionarily stable conjectures in the Cournot and Bertrand duopoly games include the ORP parameter (as in Eq. 2), i.e. depend on whether we assume the players to be altruistic, self-regarding, or malevolent. Paper IV of this Dissertation considers the "dual problem", the evolution of ORPs, and finds that the evolutionarily stable ORP depends on the assumption about the players' conjectures.

3 Results

Table 1 summarizes the contributions of each paper of the Dissertation.

Paper I studies in a laboratory experiment how the option of the Stackelberg leader of changing its decision after the follower's decision affects behavior. In this model the leader's revision of its first stage decision is costless, rendering the first stage announcement just cheap talk. We call this model the second-play game after Hämäläinen [1981]. We are interested in both how the followers use their actual first-mover advantage and how the leaders use their cheap talk announcement when they have the opportunity to cooperate due to the repeated game. Control treatments are the standard Stackelberg game without the cheap talk option

[3] It should be noted that a more complete account of an evolutionary equilibrium model would require the specification of a dynamic and its stability properties [Friedman, 1991].

and the Stackelberg game with the leader's private payoffs. We also study a treatment where the leader has both a cheap talk option and private payoffs. The subjects are given a 13×13 payoff matrix that was originally used by Huck et al. [2001] and that we also use in Paper II of the Dissertation. Many subject pairs attain the cooperative joint-optimum outcome, but rivalistic behavior is also observed. The leaders do not use the cheap talk option to their advantage but rather use it to reassure the followers of their cooperative intent. Cooperation rates are high in all treatments except when the Stackelberg game is played with the leader's private payoff information (treatment S-PI). The observation that the players cooperate in the second-play game with private information (treatment CT-PI) leads us to conclude that cheap talk can substitute the lack of payoff information.

In Paper II we correlate psychophysiological observations with behavior in a repeated Cournot duopoly game. The pairs of subjects played the game anonymously in separate rooms and psychophysiological reactions were measured from both subjects simultaneously. The subjects' ANS activity was measured with the skin conductance response and their emotional expressions were measured with facial electromyography. We also recorded their decision times. In this experiment we find that only a few of the 22 pairs reach the cooperative joint-optimum outcome. As in the experiment of Paper I, in this experiment behavior was heterogenous, as shown by the adjustments that the players made in their production quantities. Using generalized linear mixed models we find that the ANS response correlates with both observations of changes in payoffs between rounds and with the size of the adjustments that the players make in their strategies at the decision making stage. Of the emotional expressions we find that disgust and positive affect, but not anger, correlate significantly with the behavioral variables. We do not find that decision time correlates with the size of the adjustment.

Papers III and IV are closely related as they both study ORPs and conjectures by using evolutionary stability analysis. Paper III builds on previous work by Dixon and Somma

[2003], Müller and Normann [2005, 2007], and Possajennikov [2009], and finds that their results are altered if players hold ORPs that are nonzero. The finding that the evolutionarily stable conjecture depends on the ORP parameter has an interesting and unintuitive implication: For very malevolent ORPs the equilibrium quantity in the Cournot game (the equilibrium price in the Bertrand game) with the evolutionarily stable conjecture is even lower (higher) than that with the Nash or the consistent conjecture, thus making it a possible candidate as a model of cooperation(!) In Paper III we use the infinite population ESS [Maynard Smith, 1982] but the results can be straightforwardly generalized to finite populations using the concepts of finite population ESS [Schaffer, 1988] or large but finite population ESS [Neill, 2004].

In Paper IV we find that if the players in a generic two-person social dilemma game hold consistent conjectures, then the evolutionarily stable ORP is zero for an infinite size population and approaches zero from below as the finite size of a population increases. This result is compared to previous research on the evolutionary stability of ORPs [Bester and Güth, 1998, Possajennikov, 2000] that finds that with the conventional Nash conjecture assumption the evolutionarily stable ORPs are nonzero. Paper IV also contributes to the evolutionary ORP literature by employing the concept of large but finite population ESS [Neill, 2004] and shows how the evolutionarily stable ORP converges to the infinite population limit.

Paper V studies partial commitments, i.e. commitments that the players can break but only by paying a deviation cost. The paper answers to the question of how the timing opportunities are shared in an endogenous timing duopoly with price competition. This game, originally studied by Hamilton and Slutsky [1990], has two subgame-perfect equilibria (SPEs) where each of the player has the second-mover advantage, i.e. each prefer followership to leadership. We show that under asymmetric, private, and stochastic marginal costs there exists a unique SPE if a common deviation cost falls on a suitable interval. In this SPE the high-cost firm is the follower and the low-cost firm is the leader. Alternatively, when the deviation costs are specific to each firm, the high cost firm affords a cheaper commitment, i.e. has a lower left-side limit of the range of possible deviation costs than the low-cost firm.

Table 1: Contributions of each paper of the Dissertation

Paper	Research objectives	Game(s)	Method(s)	Main results
I	Study the impact of cheap talk and private payoff information on cooperation	Repeated Stackelberg and second-play Stackelberg duopoly	Behavioral experiment	Leaders do not use cheap talk to their advantage, and cooperation is less frequent without cheap talk and under private payoffs
II	Study the psycho-physiological correlates of behavior	Repeated Cournot duopoly	Behavioral and psycho-physiological experiment	Arousal in the ANS relates to reciprocal adjustments, positive affect and disgust expressions relate to bilateral gains and unilateral own gains (respectively)
III	Model the evolutionary stability of conjectures of players with ORPs	Cournot and Bertrand duopoly	Evolutionary analysis	The evolutionarily stable conjectures in the Cournot and Bertrand duopoly games depend on ORPs
IV	Model the evolutionary stability of ORPs of players with consistent or Nash conjectures	Generic two-player game	Evolutionary analysis	The evolutionarily stable ORPs are different when players have consistent conjectures than when they have Nash conjectures
V	Study how asymmetric and private cost information affects partial commitment	Sequential endogenous timing Bertrand duopoly	Equilibrium analysis	A high-cost firm affords a cheaper partial commitment than a low-cost firm, firms do not have incentives to share private cost information

4 Discussion

This Dissertation completes the current knowledge about behavior in strategic interactions and has several theoretical implications and avenues for further research.

Papers I and V suggest that imperfect commitments, such as cheap talk announcements and partial commitments, have value in strategic interactions. However, the effects of costless or partial commitments depend on available information about payoffs (Paper I) or marginal costs (Paper V). To corroborate our experimental findings more experiments with the second-play Stackelberg duopoly game should be run by allowing two-sided cheap talk options and also two-sided private information. The partial commitments studied in Paper V suggest straightforward experimental implementations and such experiments would improve the current behavioral understanding of endogenous timing in duopoly games [e.g. Fonseca et al., 2006]. By using the theory of supermodular games [Topkis, 1998] one could generalize and extend the theoretical implications of both Papers I and V.

Paper II suggests that cooperation in a repeated duopoly game has an emotional foundation. In particular, we found that the subjects show an ANS response when both players' payoffs decrease between rounds. This suggests that the theory of loss aversion [Kahneman and Tversky, 1984] has a social component in that the player is not only averse to own losses but to the losses of both players. The results in this paper and in other neuroeconomics papers that study emotions [e.g. Ben-Shakhar et al., 2007, Joffily et al., 2014] imply that theoretical conceptualizations of other-regarding behavior should incorporate emotions, as the ORP literature is rather vague about the interaction of emotions and ORPs and often relies on lay meanings of emotions. An especially interesting area of study would be how positive emotions relate to behavior in games, as recent research has discovered that positive affect increases thought-action repertoire [Fredrickson, 2004] thus suggesting a decrease in ANS activity and/or an increase in decision time. Another, methodological contribution of Paper II is its use of simultaneous psychophysiological measurements from pairs of anonymous subjects. Many experiments in the neuroeconomics literature use subject deception where the researchers impose false beliefs on the subjects about the identity of their opponents,[4] thus undermining subject control in behavioral economic experiments [Fehr, 2009]. If unbiased observations using neuroeconomics methodology are to be obtained in game theory experiments that have two or more subjects at the laboratory, techniques that overcome the need to deceive the subjects must be developed.

Papers III and IV revisit the somewhat mature concept of conjectural variations and suggest that the interaction of conjectures and other-regarding behavior in an evolutionary context may have surprising implications. Paper III highlights that the evolutionarily stable conjectures depend on the ORPs but provide unintuitive results concerning their interaction. Paper IV suggests that perhaps the often observed reduction of cooperation rates after repetitions in randomly re-matched public goods games [Gächter and Fehr, 2000] is due to the players having consistent conjectures, not Nash conjectures, in the first place. These results call for experimental verification and linking them to studies of aspiration levels where conjectures about other's behavior are explicitly elicited [Berninghaus et al., 2011, Güth et al., 2012]. Although it is impossible to observe conjectures and beliefs directly from revealed behavior and noisy to observe them from self-reports, it might be possible to study conjectures in the laboratory by proper scoring rules where the subjects are incentivized to report their conjectures truthfully [Nyarko and Schotter, 2002, Palfrey and Wang, 2009; see also Ruström and Wilcox, 2009].

[4]Examples of such experiments include the original ANS study on cooperation in the Ultimatum Game [Sanfey et al., 2003] and the correlation of the disgust expression to unfairness [Chapman et al., 2009].

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